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APPLICATIONS MANUAL

ANNEX

TO

NAS 85091

FINAL SUMMARY REPORT

PREPARED FOR

GEO. C. MARSHALL SPACE FLIGHT CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

HUNTSVILLE, ALA.

POLY-SCIENTIFIC DIVISION
Litton Precision Products, Inc.
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ENGINEERING DIVISION

APPLICATION MANUAL
FOR
CAPSULE TYPE SLIP RING ASSEMBLIES

ANNEX
TO
FINAL SUMMARY REPORT
NASA CONTRACT NO. NAS 8-5091

APPROVED BY

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Program Director

1 MAY 1966

PREPARED FOR
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

FOREWORD

This Application Manual has been prepared as part of Contract Nas 8-5091 for the "Development of Highly Reliable Capsule Type Slip Ring Assemblies" by Poly-Scientific Division Litton Precision Products, Inc. It is an annex to the Final Summary Report of that program.

The information presented is based upon the technology developed by Poly-Scientific and enlarged upon by the work of Poly-Scientific under the referenced contract. It is the intent of this manual to make basic slip ring technology known to the systems engineer. By doing so, the definition of slip rings for future applications should be more compatible with overall systems requirements and the best principles of slip ring design.

The emphasis in this manual is on reliable miniature capsule assemblies without particular regard to cost. It should be pointed out that the achievement of adequate reliability is the result of application of proven concepts and processes with stringent controls throughout the manufacture of the unit. The effort required to implement these controls results in increased unit price. The systems engineer must carefully weigh the features required against the cost and reliability demands of the system. These are important decisions since inadequate reliability is the greatest system cost. This manual will contain no discussion of the cost factors of reliability.

The organization and preparation of this manual has been directed to present a discussion of the major factors bearing upon the design of the slip ring capsule for the application. The manual starts with the discussion of the principal concepts of capsule assembly manufacture. This is followed by the limitations imposed and specific important features affecting the capsule performance. Finally, is a discussion of installation and the possible failure modes of various slip ring capsule assemblies.

It is hoped that it will serve as a basis for communications between the system designer, who must define capsule requirements, and the slip ring capsule designer, who has the ultimate design responsibility. As an aid to the systems designer, a suggested requirements sheet has been included. The data included on this sheet will enable the slip ring engineer to provide the proper balance of design to obtain the maximum performance possible from the design. The development of the best assembly for the application through effective engineering communication is the purpose of this Application Manual.

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1.0 INTRODUCTION

The slip ring and brush contact is the most simple, compact, efficient and economical method for transmitting electrical power and intelligence between components which rotate relatively. These advantages become even more significant when many circuits are required.

In its simplest concept, the slip ring is an electrically conductive ring which is rubbed by an electrically conductive material. When connected into an electrical circuit, continuous rotation of the ring is practical without interruption of the current. Slip ring assemblies are produced when a number of these rings are mounted on a shaft. An assembly of the conductive wipers is described as a brush assembly. A capsule or cartridge assembly is a self-contained unit with slip ring, brushes, bearings, and structural supports (see Figure 1).

Miniature capsule assemblies most often have their application in guidance systems for missiles and aircraft where space and reliability are at a premium. Under these circumstances every element of design is significant. Every design feature, component, material, and process must be selected by the slip ring designer to fulfill combined electrical, mechanical, chemical, and thermal requirements dictated by the desired unit performance. With so many essential requirements, superfluous or arbitrary specifications can create unnecessary complication and degrade reliability by dictating compromises of the essential characteristics.

Each supplier of slip ring capsule assemblies has techniques and processes which are inherently suited to his facilities, equipment, and skills. It is therefore unwise to expect materials, processes or designs developed and proven by one supplier to be directly applicable to another.

For important or critical applications, the system designer should discuss the requirements in detail with the slip ring manufacturer to establish the most effective criteria possible.

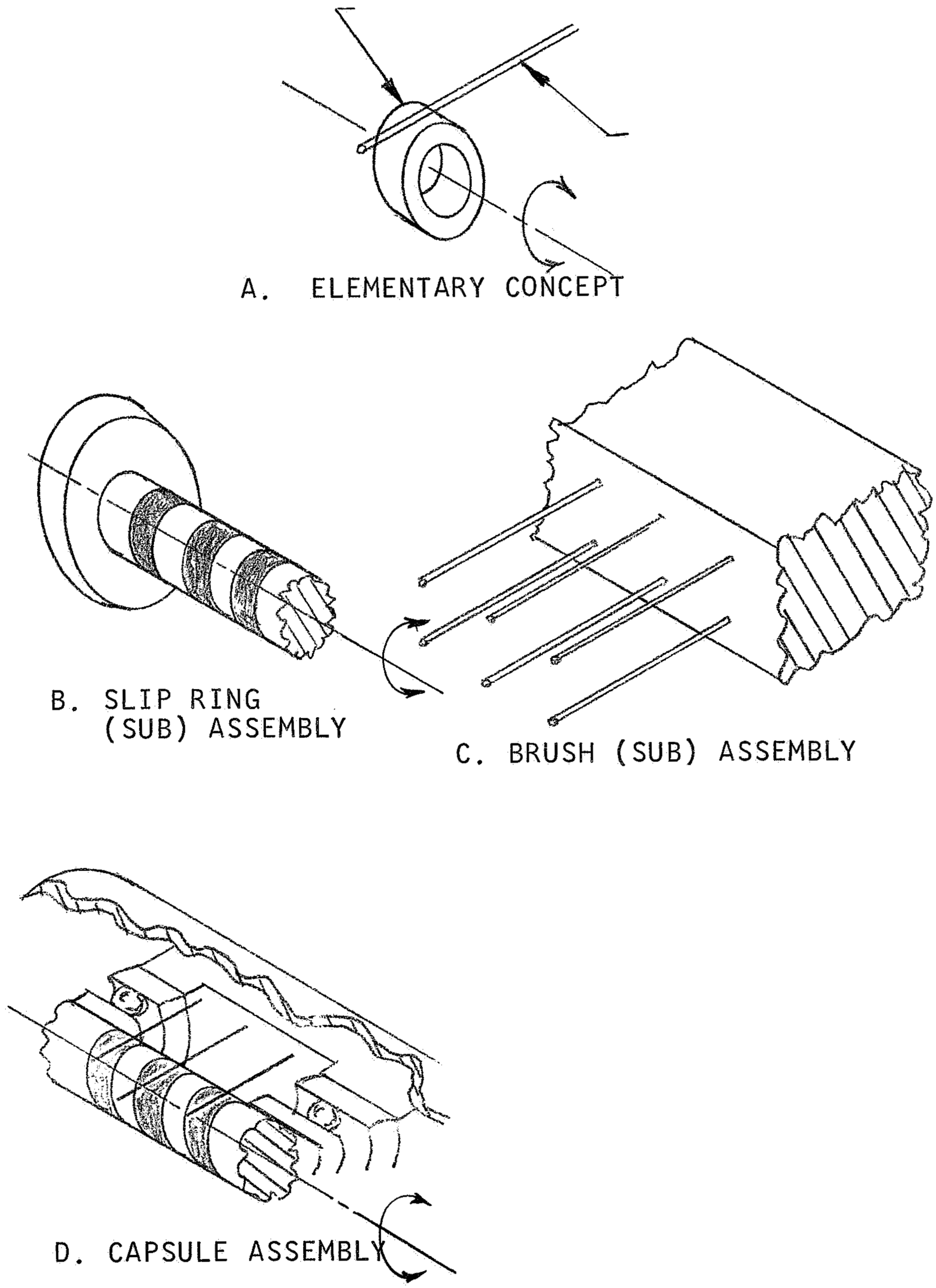


FIG. 1: BASIC DEFINITIONS

2.0 HISTORY

The use of slip ring and brushes dates back to the earliest electric motors and generators. For many years these were the only significant usage of these items. The slip rings were only minor accessories to the machines with no particular space limitations, few circuits and convenient maintenance.

With the development of airborne navigational and control equipment, the applications emphasis shifted from power to signal transmission. As a result, size and weight became critical, the number of circuits increased, and maintenance became more complicated. Instrument slip rings and brushes (Fig. 2) had to be designed and developed as specialized components for each installation. As a result of the variety of these units built, the slip ring manufacturing industry evolved to produce the assemblies.

The early slip ring industry was a manufacturing industry built around various process technologies. Slip ring manufacturers were chiefly dependent on their customers' engineering to call out configurations, materials, etc. Very little work had been accomplished on the investigation of basic design parameters in sliding contacts. The choice of material combinations, contact configurations, brush force, brush-ring alignment, brush mechanics, slip ring concentricity, brush-ring dimensional relationships, etc., were in most instances based on only partially supported opinions. A review of the requirements and performance of these separate slip ring-brush assemblies during the 1950's gave a very cloudy picture. Their use as carriers of low level signal circuits was becoming wide spread. However, their performance was so varied that any attempt at establishing a quantitative performance level was not practical. Assembly practices on the separate assemblies were so varied that performance data in specific application would vary by orders of magnitude.

During the late 1950's, the capsule type slip ring assembly (Fig. 3) was introduced, producing significant changes in the philosophy of the slip ring industry. Performance became the responsibility of the manufacturer. The leading manufacturers responded by developing essential design and engineering data for performance characteristics. The materials, processes, finishes, forces, configurations, adjustments and controls became a manufacturing prerogative and the necessary specifications and documentations were developed. With definable controls established, quantative performance levels were obtained which served as basis for further improvement.

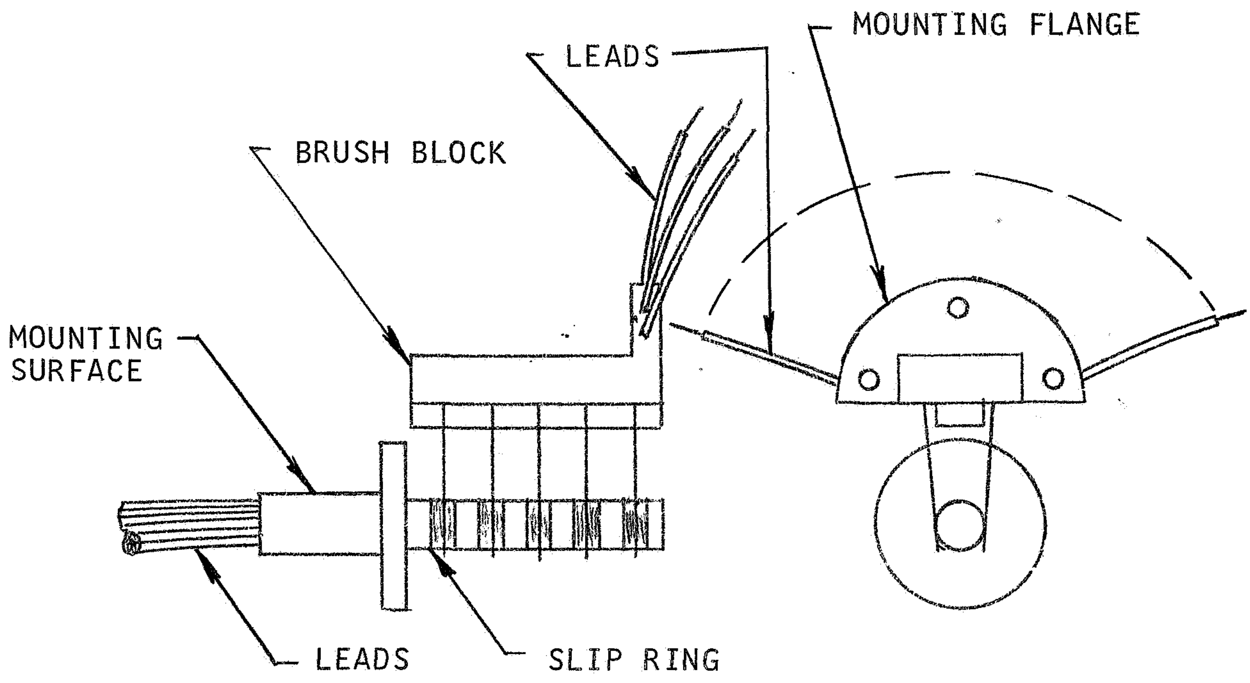


FIG. 2: SEPARATE SLIP RING AND BRUSH BLOCK (SHOWN MOUNTED)

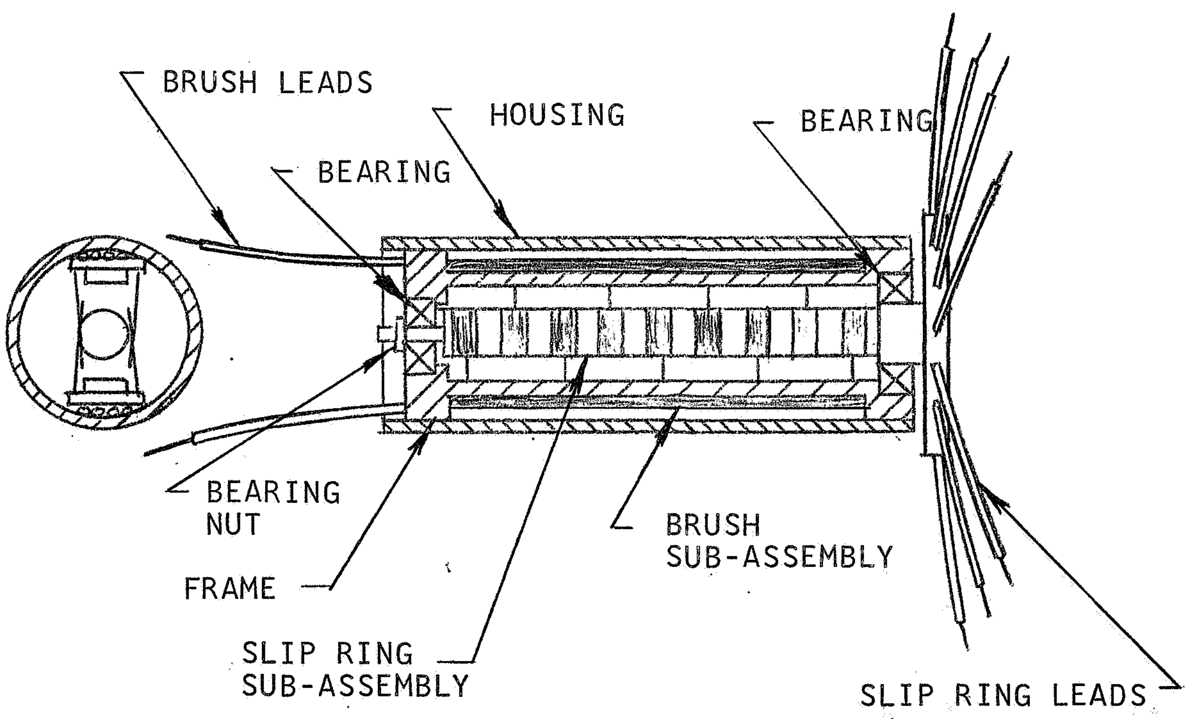


FIG. 3: CAPSULE (SECTION)

The need for increased number of circuits in a decreased size with maximum performance reliability, led to the wide usage of capsule type assemblies to replace separates in most critical applications. There were additional advantages to be gained from capsules. The capsule as a "black box" enabled the inclusion of the most up-to-date technology of design, materials, and processes in the manufacture of the unit. The concept of the capsule permitted the use of some design features with improved performance which because of handling, installation, technique or space could not be used on separates. It freed the user from a myriad of design, inspection and handling documentation of the separate (and more delicate) units. The capsule concept permitted complete pre-testing of the slip ring assembly as a component as the criteria of acceptance prior to installation.

There are still applications where separate slip ring and brush assemblies have unique features which make their use desirable for some instruments. This is particularly true where the independent installation of the slip ring or brush assembly is required. The instances are rare where such limitations prohibit use of adequately designed capsules. When separates are required, their fabrication can parallel that of capsules providing they are designed and built as matched sets.

At present, most applications for high reliability electrical conduction between relatively rotating assemblies now utilize capsule assemblies. Only the older, less critical systems or those with unique assembly problems utilize separate slip ring and brush assemblies.

3.0 COMPONENT DESCRIPTION

The major components of a capsule assembly consist of a slip ring sub-assembly, brush sub-assembly, with a frame, housing and bearings to support and enclose the unit. The slip ring and brush sub-assemblies, in principle, differ only slightly from the corresponding separates. The discussions will pertain to both corresponding components throughout this section and the remainder of the presentation.

3.1 SLIP RING SUB-ASSEMBLY

The slip ring sub-assembly (Fig. 4) consists of the rings, leads, and bearings supports which are encapsulated and insulated by a thermosetting plastic. Where design or performance dictates, mounting members, flange or backshaft, and reinforcing elements are included in the assembly.

The rings are conductive metal rings arranged concentrically on a cylindrical (drum type) or flat (pancake type) surface. The outer surface is unencapsulated and is normally finished to receive a conforming brush. Lead wires connect to each of the rings and extend to a termination outside the slip ring sub-assembly.

Bearing seats are provided at each end of the slip ring axis. These seats may be part of any reinforcement used in the assembly or they may be simply embedded in the assembly. The inboard (near the lead) seat is usually designed as an integral part of a flange or backshaft which serves as the drive mechanism for the slip ring. The outboard seat normally includes a threaded member for capsule assembly and end play adjustment.

The entire slip ring is insulated and bound into an integraded body by a thermosetting plastic. This plastic serves as the principal strength member for slip rings of the smallest possible diameter.

A reinforcing member is required in the slip ring when the plastic does not have adequate strength and rigidity to support the assembly. The most effective reinforcement consists of a one-piece member of maximum rigidity incorporating bearing seats, and all other structural features.

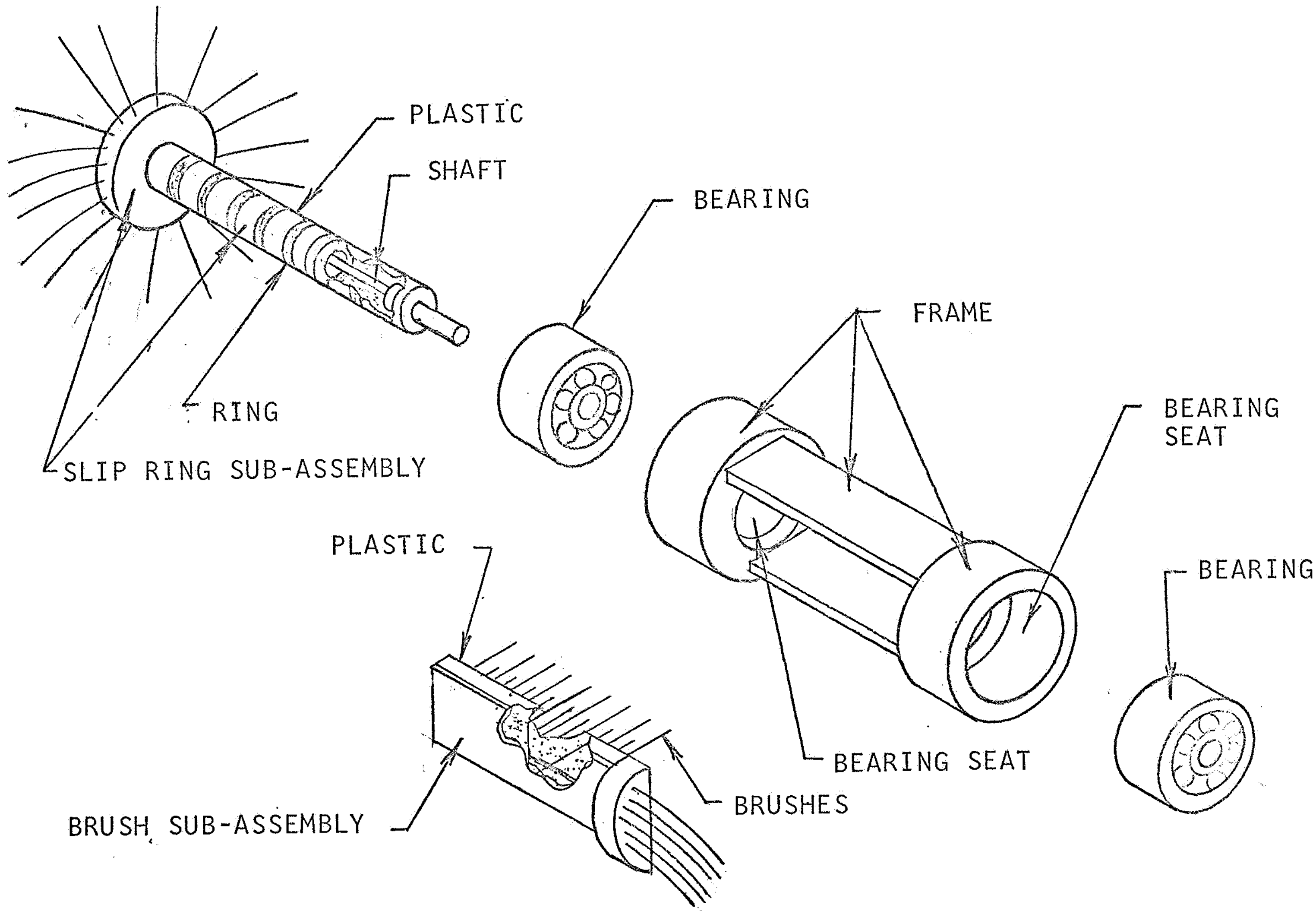


FIG. 4 - CAPSULE COMPONENTS

3.2 BRUSH BLOCK SUB-ASSEMBLY

The brush assembly (Fig. 4) consists only of brushes, their connecting leads and the supporting plastic. Seldom are supplemental components used in the brush assemblies.

The brushes in miniature capsule assemblies are normally made of small diameter alloy wire formed into a shape which will allow at least two wipers to rub the ring surface. Physical contact is maintained by the spring force of the brush. Lead wires may or may not be encapsulated into the brush assembly, depending upon the concept and design. In some concepts, junction bars are included to provide connections between brushes and leads. The entire unit is bound together with plastic. Most brush sub-assemblies are limited in space and do not contain metallic reinforcement, however, many do include glass fibre reinforcement for the plastics. As in the slip ring sub-assembly, the plastic insulates the metallic components.

3.3 ASSEMBLY COMPONENTS

The principal structural member of the capsule assembly is the frame. It has two or more longitudinal members which provide strength and rigidity for the stator and support the brush assemblies. The frame has provisions for ball bearings which provide the alignment and concentricity for the slip ring sub-assembly.

The rotor and stator of the capsule assembly are connected by ball bearings mounted on the slip ring and into the frame. The take-up of play in these bearings is adjusted and fixed by the position of the bearing nut which holds the capsule assembly into a single functioning item of hardware (Fig. 3).

The capsule is shielded and protected by a housing which encloses the brush sub-assemblies.

4.0 DESIGN CONCEPTS

There are nearly as many capsule designs as there are slip ring applications. To meet these requirements, there are several concepts which are used in slip ring sub-assembly and brush block sub-assembly design.

4.1 SLIP RING SUB-ASSEMBLY

There are three (3) generally accepted concepts for the manufacture of the slip ring sub-assembly (rotor). These are: stacking, casting (molding) and electrodeposition. We shall consider each of these processes.

4.1.1 Stacking - Stacking (Fig. 5) is essentially a process of assembling and cementing pre-formed slip ring components into a single element. Such a process requires the machining of shafts, insulators, barriers and rings to extremely close tolerances to prevent the stack-up from creating cumulative out-of-tolerance conditions.

This process has its greatest advantage for slip ring sub-assemblies required in small quantities since this process avoids the manufacture of expensive tooling. The process is most practical in larger diameter assemblies where casting or molding processes become less suitable.

In view of the requirements for close tolerance machining, stacking has several disadvantages. These tolerances require easily machinable materials and limit the choice of both plastic and metals. In small diameter units, the component size-to-tolerance ratio makes manufacture difficult. The location of multiple leads within slots on very small shafts becomes impractical or impossible.

4.1.2 Casting - Slip ring sub-assemblies can be produced by casting. (Fig. 6). The rings and attached leads are positioned into an accurately grooved mold. If a reinforcing member is required, it is inserted in the mold with proper alignment and the mold is filled with the desired plastic.

The casting process has the advantage of permitting the use of any metal or alloy which can be formed into the ring shape. It has further advantages in that it is a very practical concept for use with most large scale production orders. In this process any plastic, filled or unfilled, can be used since very little machining of the plastic must be done.

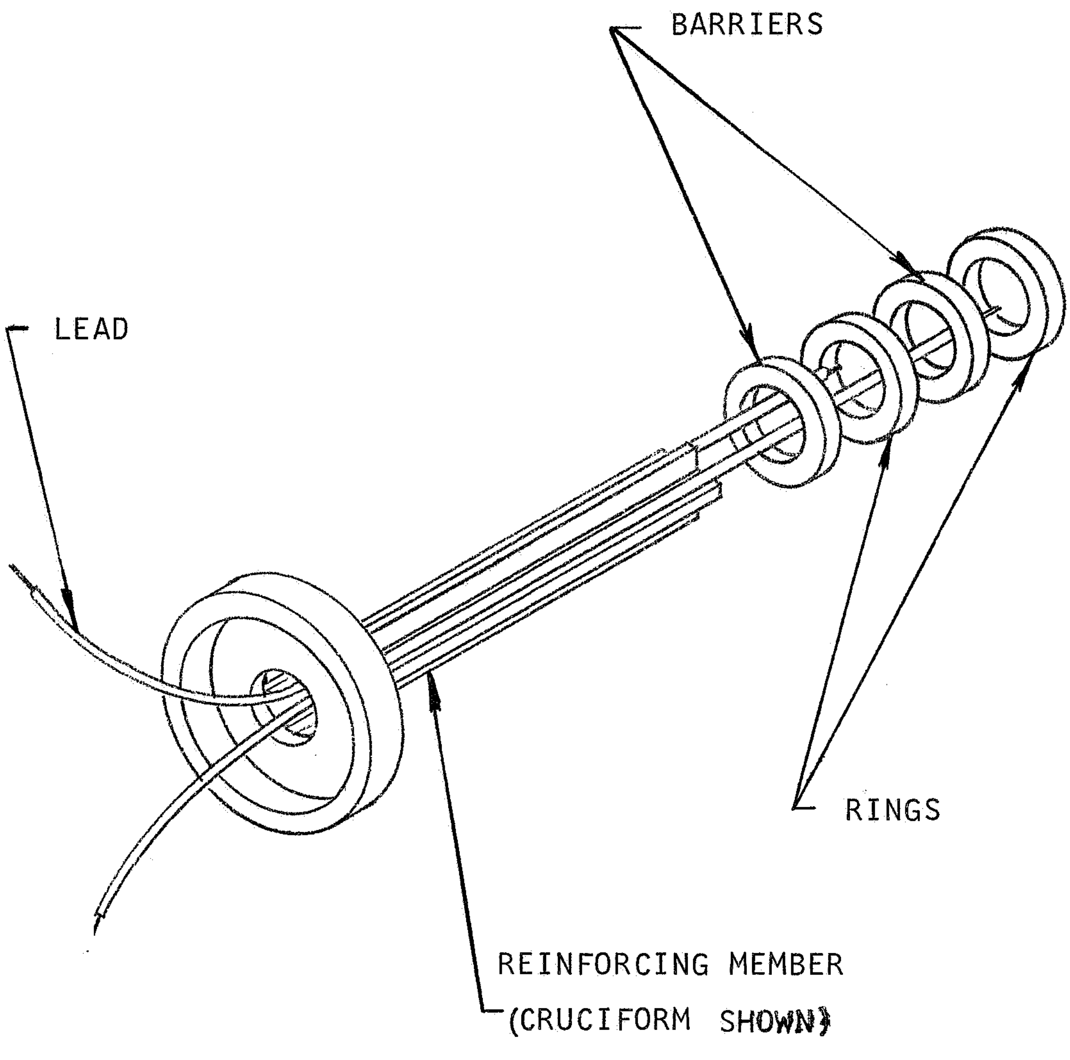
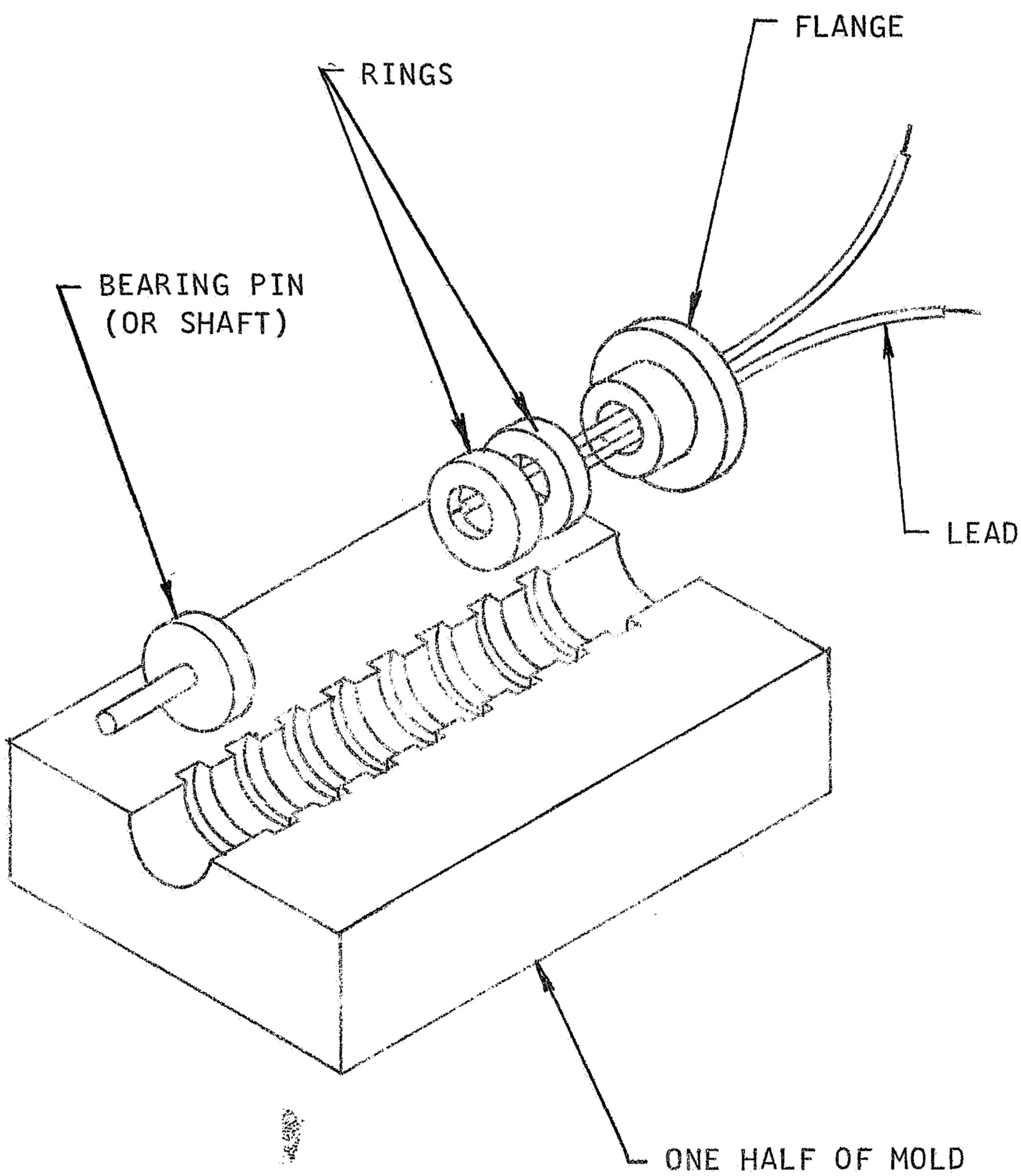


FIG. 5 : STACKED SLIP RING



PLASTIC IS CAST OR MOLDED INTO SPACES BETWEEN COMPONENTS.

FIG. 6: CAST CONCEPT FOR SLIP RING

Casting offers a major advantage in the use of any type ring material, either pure metal or alloy.

The principal disadvantage of the casting process is that the accuracy of the ring location is dependent upon the several tolerances on the ring, on the grooves in the mold, and on the plastic properties. Once the mold is accurately made, the ring location depends only upon the tolerance of the rings and the plastic properties.

This concept has a disadvantage of potential voids because it requires filling the narrow barriers between rings. This is particularly true with high viscosity, or highly filled plastic systems.

Although casting is normally done using a liquid casting resin of a thermoset type, the same concept can also be used with transfer molding or thermosetting compounds using essentially the same processes.

4.1.3 Electrodeposition - Electrodeposition (Fig. 7) is a combination of processes which include the casting of plastic around the structural shaft member and the lead wires; the grooving of the plastic for rings, the establishment of a metal surface at the bottom of the groove making contact with the proper lead wire; the plating of ring material into the groove to build-up the ring; and the final machining and surface finishing of the ring itself.

The electrodeposition process can be used on slip ring sub-assemblies of virtually any size. The principal advantage of electrodeposition is that it permits accurate placing of the rings. The location of the rings in the electrodeposition process is the most accurate of any method known for slip ring manufacture. The electrodeposition process coupled with precision groove grinding lends itself very effectively to any type of plastic, filled or unfilled, which may be desired for the construction of the rotor.

The electrodepostion process has the disadvantage of being limited to only those ring materials and alloys which can be reliably electrodeposited. There is the additional disadvantage of the electrodeposited ring to lead joints. These are extremely dependent upon the control of process for adequate strength and uniformity.

4.2 BRUSH AND BRUSH-BLOCK SUB-ASSEMBLY CONCEPTS AND FEATURES

There are principally four (4) types of brush assembly concepts which are used in the stators of capsule assemblies. These four are: stacked, cast, floating and pre-stressed.

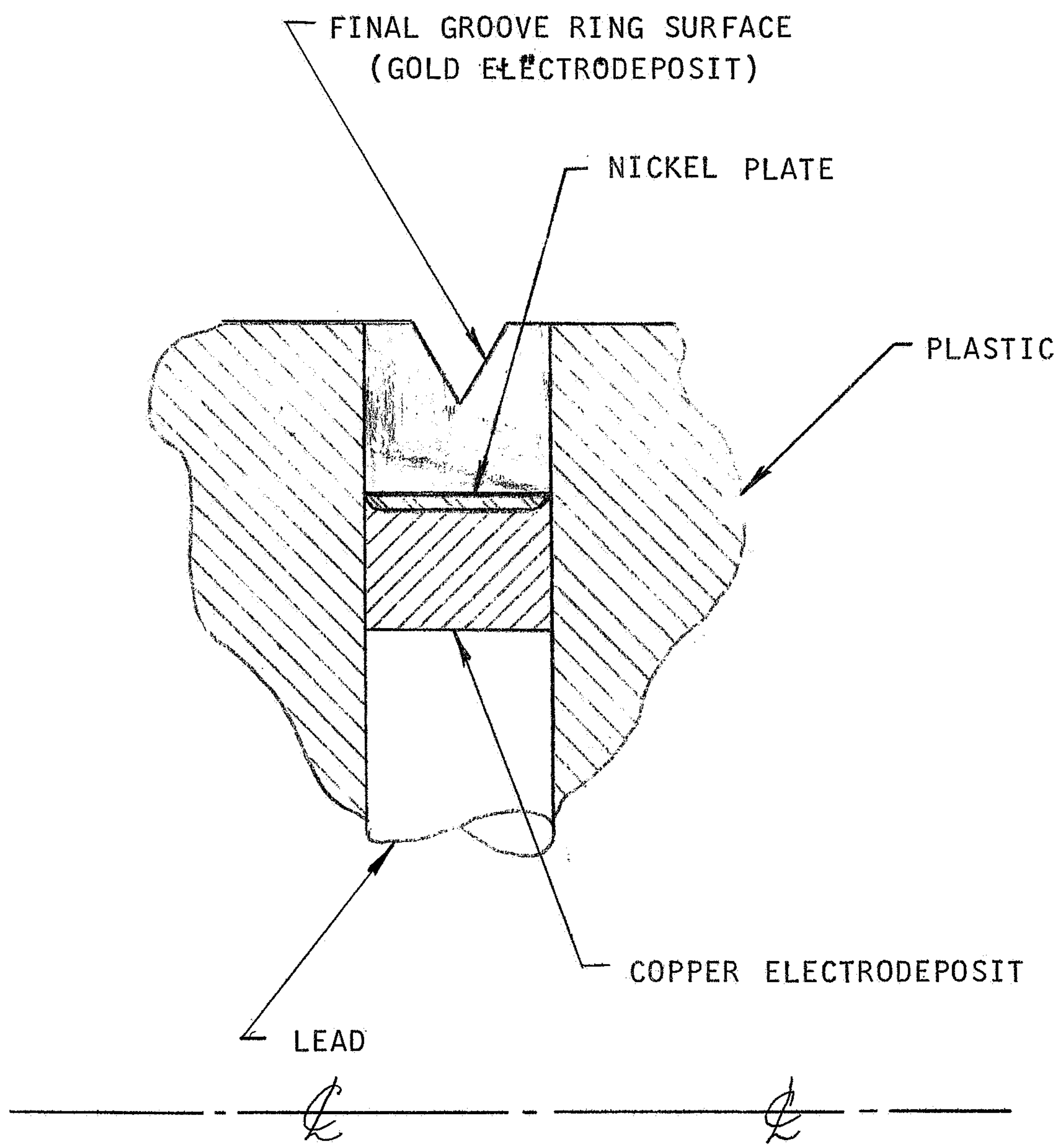


FIG. 7 : ELECTRODEPOSITED TYPE RING

4.2.1 Stacked - As the name implies, the stacked brush assembly (Fig. 8) is built up by a series of wafers. The brushes are positioned in grooves or slots in the wafers. These wafers are designed to confine the brush so that it is free to move about on the ring without leaving the ring.

The large amount of motion permissible between brush and ring in several directions does not allow the brush to produce a fixed wear path on the ring, and therefore can create an unstable and frequently noisy assembly. In addition, the unsupported brush-lead joint can contribute possible noise and circuit breakage, since the brush motion creates a strain on this joint. This concept does offer the advantage of having very low torque under conditions of oscillation since the brush can move through a few degrees without sliding on the ring. This type of brush assembly design is not being used in modern brush assemblies.

4.2.2 Floating Brushes - The floating-brush type assembly (Fig. 9) consists of a series of tubes positioned perpendicular to the axis of the slip ring assembly. Each of these tubes is electrically connected to one of the lead wires. The brushes are four small diameter wires which fit accurately into the bore of the tube. The brushes are approximately in the form of a dog leg so that one end of each brush rides in one of the two grooves of the ring, and the other end is in the tube. The restriction of the brush by the groove and tube prevents the four brushes from moving within the tube and maintains the position on the ring.

A principal advantage of this assembly is its small brushes of short length which gives it capability to fit into very small diameter capsule units. Another advantage for the floating brush is the absence of a brush-lead joint eliminates the need for brush material weldability and solderability. It has one additional advantage in that there are four wipers for each ring, thereby improving the redundancy of contacts for the brush assembly.

The disadvantages lie in the fact that the wipers must approach the ring with a slight angle since the centerline of the tube is positioned halfway between the two grooves in which the two sets of brushes slide. Also there is an increased variation in ring resistance due to the fact that the wipers contact the ring approximately 90° apart instead of the 180° between contacts for other brush block concepts. This brush concept has an additional disadvantage because each wiper has two pressure type electrical contact in series, one on the ring and one in the tube.

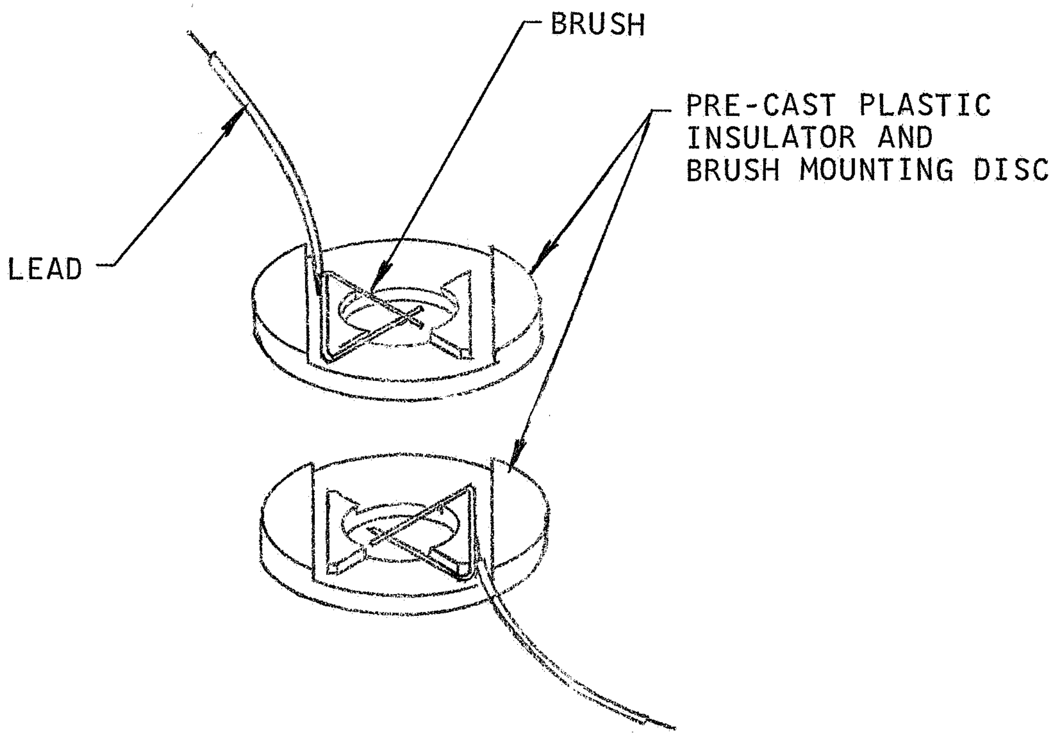


FIG. 8 : STACKED TYPE BRUSH ASSEMBLY

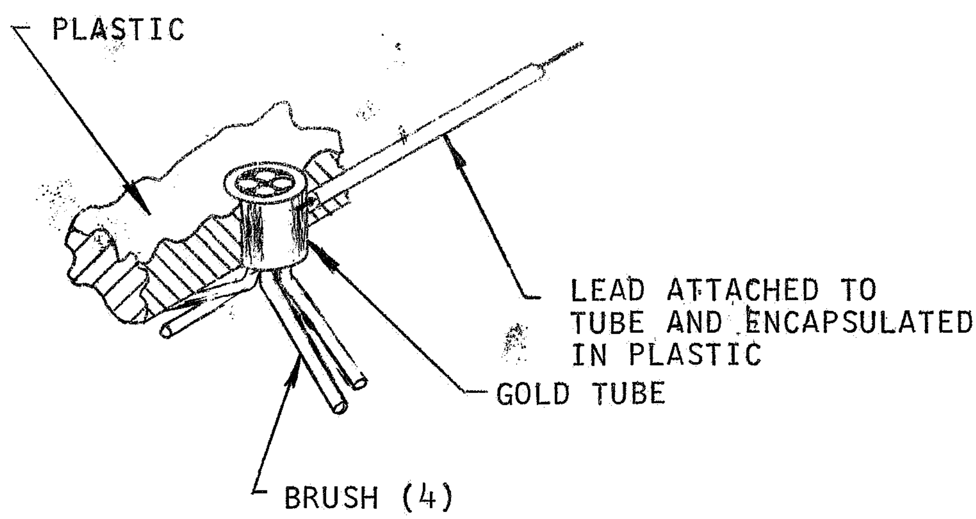


FIG. 9 : FLOATING TYPE BRUSH

4.2.3 <u>Cast</u> - By far the simplest and most extensively used brush assembly concept is the cast assembly. (Fig. 10). In the cast brush assembly the brushes with their attached leads are loaded into a mold through a series of holes or slots. The leads or terminals are routed to and held in fixed positions in the mold. The mold is then cast with plastic (or molded with a transfer molding compound.)

The completed cast brush assembly is a very rigid unit with the brush location precisely determined by the tooling and plastic characteristics. This allows the brush assemblies to be easily removed and replaced with little chance of damage. Such removal permits independent sub-assembly cleaning and inspection.

After the removal from the mold and the finishing of any required surfaces, the brushes must be straightened and adjusted to achieve the proper brush force and spacing required by the assembly design. It is in this area that the cast brush assembly has its principal weak points. The accuracy of location of the brushes is first affected by the location of the holes in the mold through which the brushes must pass; second, by the location of the brushes within the holes, and third, by the contraction or shrinkage of the plastic from the nominal mold dimensions as the plastic cures. The combination of these tolerances can result in a significant inaccuracy of brush position. The cast concept increases the amount of handling to which the brushes are subjected and as a result scratched or nicked brushes sometimes become a problem. Also, forming of brushes is required after heat treatment, introducing undesirable residual stresses. This concept requires more tooling than other brush block concepts; consequently, it is limited to high quantity production. The brush misalignment possible by the use of this design concept can result in axial loads on the rings and produce increased torque.

4.2.4 <u>Pre-Stressed</u> - A brush concept widely used in miniature capsule assemblies is the pre-stressed type brush design (Fig. 11-A). (This is also know as the "Nooteboom" design). Two types of pre-stressed brush assembly designs are in use today. The simplest type consists of a plastic insulator mounted on the frame. This plastic insulator is grooved to position the brushes in the approximate location with respect to the ring.

The brushes are triangular shaped when observed in the free position with the contact points near the open vertex. The brush, when opened up, locates on the brush block and on the slip ring in the most relaxed position with respect to the groove on the slip ring, the groove on the brush block, and its own compliance. The brush is then fixed by cementing it to the brush block. The accurately positioned brush, therefore, has the best alignment possible without

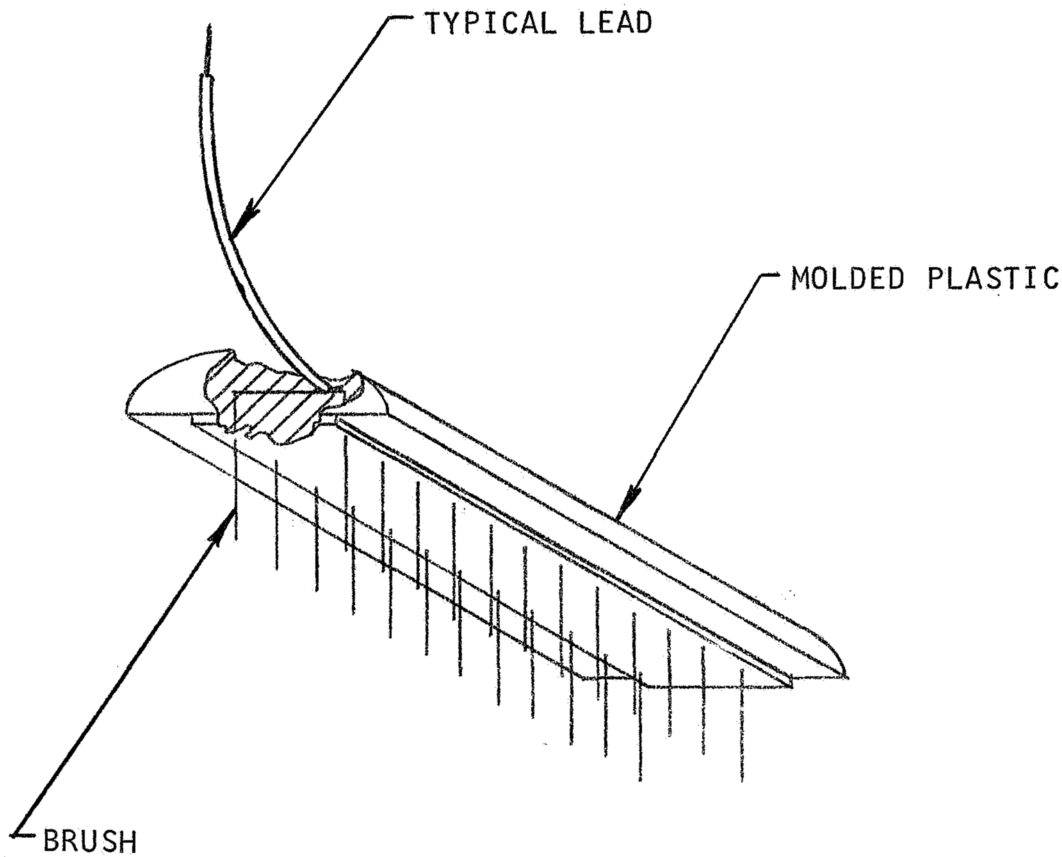


FIG. 10: CAST TYPE BRUSH BLOCK

axial loads since the brush is fixed in the final assembly stage.

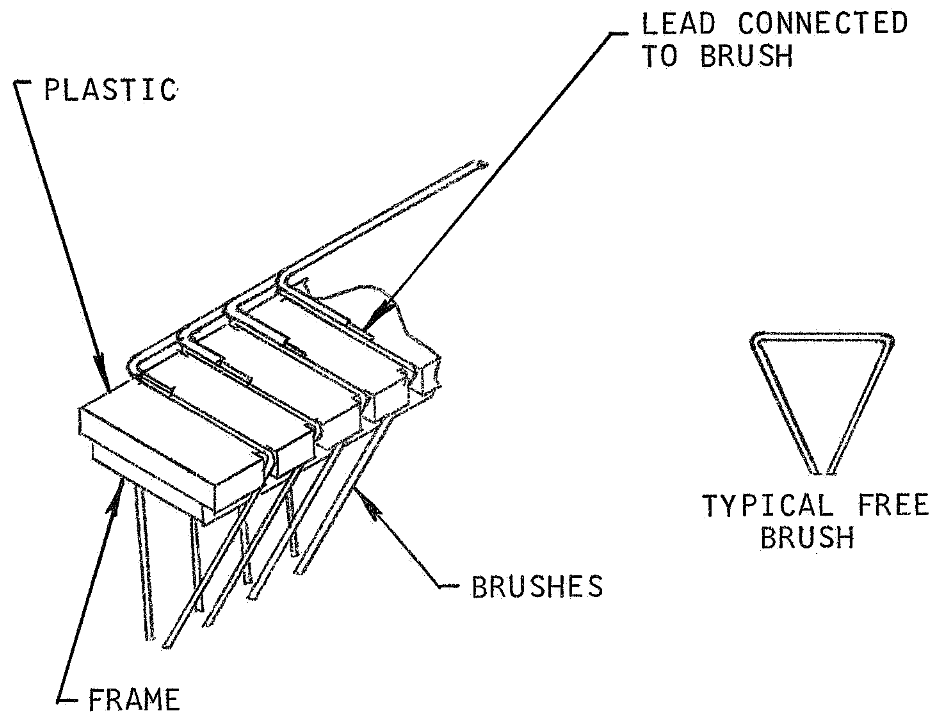
This concept has several other desirable features. It permits heat treatment of the brush after final forming, therefore minimizing the residual stresses. The brush undergoes less handling than in other concepts. These two advantages combine to offer the most reliable brush from a mechanical standpoint. Due to the increased deflection of the brush per unit of force at the time the brush is formed, this concept requires less precision of the setting diameter than other brush concepts.

Certain disadvantages stem from this concept. The simple pre-stressed design utilizes cement to hold the brush in place, and the leads are soldered to the brush after this cement is cured. The connection is then covered with plastic to prevent electrical failures during use of the part. The curing of plastics and the soldering of brushes on the slip ring introduce undesirable contaminants to the rings requiring subsequent cleaning operations for their removal. In this type of brush block, the leads are always external to the brush assembly proper, and are confined between stator members and the cover of the assembly. For this reason, precautions must be taken to prevent the leads from distorting or damaging the brush assembly.

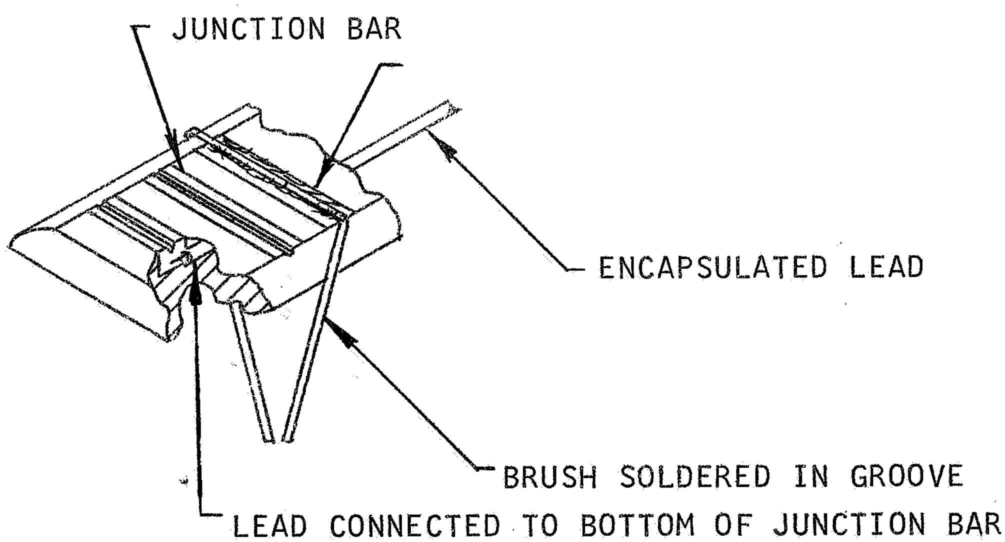
In the more advanced junction plate pre-stressed design (Fig. 11-B), the lead wires are connected to a metal junction bar and totally encapsulated in the plastic brush assembly. The brushes are soldered to the outside of the junction bar. The locations are determined by the V-grooves, the junction bar and their respective alignment with grooves in the slip ring. Both types of pre-stressed brush blocks offer this same simplicity of assembly, the same minimum damage to the brushes due to handling, and forming. The junction plate type offers the distinct advantage of having leads encapsulated in plastic, therefore in a predetermined position, and in addition it offers the maximum accuracy of alignment since the grooves can be precisely placed and inspected to verify the accuracy of the work. Furthermore no plastic operations are required after brush installation.

4.3 RECOMMENDATION

The maximum precision and reliability of a miniature capsule assembly results from a slip ring sub-assembly built to the electrodeposition concept combined with a pre-stressed brush assembly of the junction plate type.



A: SIMPLE PRESTRESSED TYPE



B. JUNCTION PLATE TYPE

FIG. 11: PRESTRESSED BRUSH ASSEMBLY

5.0 MATERIALS

The manufacture and use of miniature slip ring capsule assemblies require some exceptional combinations of material properties and characteristics. The materials and their properties are discussed in this section.

5.1 LEAD WIRE

Most capsule designs require lead wires for making electrical connections to the circuits. Since the capsule end of the lead is normally embedded in the plastic, the leads must be subjected to much or all of the many processing operations of capsule manufacture. These processes expose the leads to a multiplicity of mechanical, thermal and chemical treatments which most wire uses do not require. It is therefore imperative that the materials used for the conductor and the insulator be the best possible to insure capsule reliability against lead failure.

5.1.1 Conductor - The most frequently used conductor material is copper due to its mechanical and electrical characteristics. Both electrolytic tough pitch (ETP) copper and oxygen free high conductivity (OFHC) copper are used, with the only difference between the two being the oxygen content of the conductor. The oxygen free conductor has less tendency to undergo galvanic corrosion and consequently is more suitable for over-plating. In addition, oxygen free conductor has better weld characteristics than ETP copper.

The main disadvantage of using copper as a conductor is that it corrodes when exposed to oxidizing atmospheres. Therefore, it is necessary to protect the copper by plating its surface with a more stable material. Two such materials are commonly in use - silver and nickel. Silver has become the more popular of the two because of its properties. The elongation of silver is 50%, that of nickel 30%, compared to 38% for the copper; thus, silver is more able to withstand extensive flexure than nickel. Silver plated leads have a 30% to 40% greater flex life than nickel plated leads.

Plating materials commonly used on copper wire for other applications (such as tin, cadmium, etc.) are generally suitable for slip ring applications because their melting points are below that which the conductor must withstand during lead wire manufacture.

The plating of the conductor introduces an additional problem. Where ever there is an imperfection in the plating, the two dissimilar metals can react like a galvanic cell in the presence of moisture. In the use of silver plating to prevent oxidation, imperfections in the plate will cause the copper to oxidize to form cuprous oxide (commonly called "Red Plague"). Plating and lead wire processing must be controlled to insure reliable lead wire. The use of 55 microinch plating thickness, instead of 40 microinch as called out in MIL-W-16878-D, greatly reduces the probability of breaks in the plating.

There are three principal choices for the number of strands to be used in lead wires of the AWG size normally used. These are single, seven and nineteen strands. Nineteen stranded lead wire is superior to single or seven stranded lead wire and is being used almost exclusively because of its increased flexibility. A construction available in larger gages has the lay of all strands in the same direction - as opposed to existing nineteen stranded lead wire which has two concentric layers of stranding with the lay of the outer strands opposite in direction ot the inner core. Should this become available and be proven feasible for slip ring use, it will be an additional improvement to the flex life of the leads.

At present, the silver plated copper conductor is by far the most frequently used conductor for use in capsule assemblies; however, further studies are being made for the development of a more reliable conductor. The use of a high silver alloy conductor is being explored as a possible replacement for the silver plated copper.

5.1.2 <u>Insulation</u> - The lead wire insulation to be used must be capable of withstanding the necessary processing of the assembly. In order to meet the insulation requirements of the system, it must be clean, tough, and resistant to process chemicals. TFE Teflon has proven its capability to meet these requirements, and is being used almost exclusively for capsule lead wire insulation.

Two types of Teflon insulation are available. One is the wrapped Teflon tape; the other is the extruded Teflon. Several problems with the use of wrapped insulation have resulted in the use of extruded Teflon insulation. Wrapped insulation can, if not properly sintered, unwrap. In addition, painted on color coding stripes frequently used with wrapped tape have a tendacy to flake off. The outside surface of the wrapped insulation is nonuniform and tends to collect foreign particles.

Extruded Teflon insulation is better suited for capsule applications, presenting a smooth surface not requiring tracers or other surface imperfections which can shed particles.

Clear insulation has proven superior to colored because the pigments used in coloring the Teflon are detrimental to uniform cure. Clear Teflon also allows visual inspection of the conductor plating and condition.

5.2 CONTACT MATERIALS

Proper selection of and use of contact materials is of prime importance to an assembly. Generally, it has long been recognized that only precious metals can be considered for use in miniature capsule assemblies. Ideally, the most noble of metals should be used for most reliable operation insofar as corrosion resistance is concerned. Commensurate with other significant properties, this metal should be relatively hard and have a high melting point for better wear resistance. It should have a high reaction resistance to all environments in which it is to be used, to avoid formation of insulating oxides, sulfides, organic compounds, etc. It should have a high current carrying capability and good machinability. The brush material should have all the foregoing characteristics, and in addition, the brush must have good spring-forming characteristics such as a high creep limit. Unfortunately, metals or alloys that meet all of these requirements do not exist and compromises must be made for each application. These are made on the basis of noise, torque, wear, and reliability requirements for each design. The properties of several frequently used contact materials are listed in Table I.

The most nearly satisfactory ring material has been found to be pure gold. This is principally due to its inert character with respect to both the inorganic reactions and organic polymerization. Its major problem lies in its low hardness. This is largely overcome by the electroforming methods which can produce pure gold rings to the highest possible hardness (Knoop 125). Additional techniques include the use of 98.4% purity gold surfaces to values up to 200 KHN.

The brush material often used in contact with the gold for highest reliability contacts is the 95% Au, 22% Ag, 3% Ni which has minimal tendencies to become corroded or to catalyze organics.

5.3 DIELECTRIC MATERIALS

The performance of the assembly can be greatly affected by the properties of the dielectric material. The critical properties span the full range of chemical, mechanical, thermal and electrical characteristics. Chemically, the plastics must be stable with a minimum of outgassing and bleedout when exposed to the chemical fluids in processing or system environments. Mechanically, they must have the strength and rigidity to reliably support the sub-assemblies under the forces applied by machining operations, performance

TABLE I

REPRESENTATIVE CONTACT MATERIALS

TRADE NAME	NOMINAL COMPOSITION (weight %)	TEMPER	SPECIFIED HARDNESS(range) (Knoop-100g)	TENSILE MODULUS OF ELASTICITY ($\times 10^6$ psi)
Coin Gold	90 Au 10 Cu	A CW	108-132 162-198	-------
Neydium 90 Coin Silver	90 Ag 10 Cu	A CW1 CW2	68-83 108-132 144-176	12.5
Ney Oro 69 Leach & Garner 201 Baker #416 West. Elec. #1 Wilson G 14	69 Au 25 Ag 6 Pt	A CW	81-99 135-165	11.4
Paliney 7 Leach & Garner 226 Baker 1560	35 Pd 30 Ag 14 cu 10 Au 10 Pt 1 Zn	A HT	187-253 324-396	17.0
Ney Oro G Leach & Garner 205 Baker 5348	71.5 Au 14.5 Cu 8.5 Pt 4.5 Ag 1.0 Zn	A CW HTA HTW	180-220 216-264 288-352 315-385	16
Ney Oro 28A Leach & Garner 212 Baker 8227	75 Au 22 Ag 3 Ni	A CW1 CW2	90-110 126-154 162-198	11.0
Platinum Gold	98 Au 2 Pt	A CW	- 72-88	----
Electrodeposited Gold	99.7 Au (Min.)	---	110-140	8
10 Carat Gold	41.7 Au 36.2 Cu 12.8 Ag 9.3 Zn		----- 225-275	----
Baker 7872	90 Pt 10 Ru	A CW	198-242 252-308	33.4
Baker 158	85 Pt 15 Ir	A CW	180-220 225-275	26.3
Fine Silver	99.90 Ag (Min.)		---- 99-121	10.3 11.3
Silver Graphite	I:50 ag-50C II:80 Ag-20C III:90 Ag-10C IV:93 Ag- 7C V:95 Ag- 5C	none	----	----
14 Carat White Gold	58.3 Au 23.5 Cu 12.2 Ni 6.0 Zn	A CW	153-187 180-220	----

TABLE I (CONT'D)

TRADE NAME	MINIMUM (*) ULTIMATE STRENGTH (X 10³ PSI)	MINIMUM ELONGATION (%)	RESISTIVITY (ohm-cmf)	ELECTRICAL CONDUCTIVITY % IACS	MELTING POINT (°F) (SOLIDUS)
Coin Gold	----	----	67	15.5	1710
Neydium 90 Coin Silver	40 60-80	30(2")	12.5	83.0	1430
Ney Oro 69 Leach & Garner 201 Baker #416 West. Elec. #1 Wilson G 14	40 60	30(2")	95	10.9	1885
Paliney 7 Leach & Garner 226 Baker 1560	100 150-155	10-18(2") 2-(2")	210 190	4.9 5.5	1985
Ney Oro G Leach & Garner 205 Baker 5348	75-80 --- 125-130 140-150	10-15(5") ---- 4-5(5") 2(5")	135 125 87 87	7.7 --- 13	1750
Ney Oro 28A Leach & Garner 212 Baker 8227	40-45 75-80 85-90	10(2") --- ---	73	14.2	1920
Platinum Gold	24 38	55(10") 1(10")	72 --	14.4	2000
Electrodeposited Gold	----	----	27	38.5	1945
10 Carat Gold	----	----	--	----	----
Baker 7872	60-80 145	30(2") 2(2")	259 ---	4.0 ---	3270
Baker 158	55-65 110	20(2") 5(@4B&S)(2")	180 ---	5.8 ---	3250
Fine Silver	18.2-24 ---	48-54(2") 5(4B&S)(2")	9.7 ---	107.0 ----	1761
Silver Graphite	---	----	---	0.53 11.5 30.0 45.0 55.0	----

(*) Range indicates different Minima reported by different vendors.

loads and temperature changes. Thermally, the material must have a temperature resistance and expansion coefficient which avoid degradation or failure due to high or prolonged temperatures. Electrically, the plastic must have sufficient dielectric strength to prevent breakdown between uninsulated components and adequate volume and surface resistivity to insure high values of insulation resistance between closely spaced conductors. Unfortunately there is no one ideal plastic.

Fortunately, there are plastics which have been proven suitable for many applications. For capsule assemblies, these plastics are almost always thermosetting materials. Polyester, diallylphthalate, and epoxy resin systems are widely used. The specific choice is usually defined by the application requirements and slip ring manufacturers' processes.

Epoxy resin, highly filled with lithium aluminum silicate, has been found to be a most reliable material for low coefficient of expansion and outgassing while having high electrical properties and mechanical rigidity. (See Table II)

5.4 BEARINGS

Bearings used in capsule assemblies are almost invariably high precision ABEC-7 ball bearings. The high quality ball bearings are required in order to have low friction and to achieve precise alignment between rotor and stator.

The materials of the bearings are 440 C stainless steel for balls and races and 300 series stainless steel for retainers. Even in the low load and low speed application of most slip rings some bearing lubrication is necessary. This lubricant is normally a light weight oil which is applied in very low quantities to minimize contamination of the electrical contacts.

Ball bearings with two different types of retainers are presently in use on most capsule assemblies. These are crown type and ribbon type retainers. Both have proven suitable for most applications, but ribbon retainer bearings are more reliable than bearings with crown retainers for the minimum lubrication applications.

5.5 STRUCTURAL MATERIALS

By definition, structural components are expected to provide the strength and support for the capsule assembly. The materials used in these components are chosen on the basis of their strength, modulus of elasticity, corrosion resistance, and relative coefficient of expansion. For most requirements, this boils down to aluminum alloys and stainless steels. Aluminum is preferred for larger assemblies

TABLE II - PLASTICS PROPERTIES

	Polyester	DAP	Unfilled Epoxy	Filled Epoxy (E.S. 218)
Dielectric Strength, Volts/Mil	280-400	400	400-500	300-400*
Arc Resistance, Seconds	125	145	120	120*
Volume Resistivity, Ohm-Cm	10^{14}	10^{9}	10^{12}-10^{17}	10^{12}*
Coefficient of Linear Thermal Expansion (In/In/°C. X 10^{-6})	55-100	32	60-70	17.1
Tensile Strength, PSI	6-13,000	8,000	10-13,000	14,400
HDT**, °C	60-225	232	46-288	152-201
Modului of Elasticity, (PSI X 10^{6})	.3-.64	1.3	.3-.5	2.87

* Estimated Value

** Dependent upon curing system and curing conditions.

where weight is a prime consideration or where high expansion plastics must be used. Stainless steel is preferable in miniature assemblies using highly filled plastics where space and rigidity are the principal objectives. Good practice dictates that all structural metals of a capsule have equivalent properties. (see Table III)

TABLE III - PROPERTIES OF STRUCTURAL METALS

	2024T4 Aluminum	303 Stainless Steel
Coefficient of Thermal Expansion (Microinches/in/°C)	23.2 (20 to 100°C)	16.2 (0 to 100°C)
Tensile Strength (1000 PSI)	68	80 to 90
Modulus of Elasticity (Million PSI)	10.6	29

6.0 DESIGN CONSIDERATIONS

The previous sections have introduced the capsule assembly, its terminology, the concepts of its design and the materials most frequently used in it. This section discusses the performance conditions and information requirements to develop an effective assembly. Although each of these topics may be treated individually, there are many interrelating requirements which must be considered collectively for a reliable item of hardware.

6.1 MECHANICAL CONSIDERATIONS

6.1.1 Dimensional - The first limitation normally imposed upon a capsule design is the available size and shape. Space is always a critical item in most system designs. For capsule assemblies, too often limitations are placed upon the dimensions which impose restrictions upon the performance of the device. Limited space is therefore often a contributing factor to the failures of the units.

This should not necessarily be the case if adequate space allowance is made at the time of initial system design. Figure 12 and 13 show curves of recommended dimensions for the capsule barrel (i.e., the cylindrical portion containing rings and brushes. These dimensions indicate minimum dimensions for maximum reliability. Reductions in size may require compromises of one or more optimum features. Smaller capsules can of course be built with the basic reliability for their applications. For maximum reliability, dimensions at or near those indicated will allow for proper design of all components.

6.1.2 Lead Wire - Lead wires occupy more volume within the capsule assembly than any other component. The gage and number of leads required greatly affect the dimensions of the assembly. Figure 14 shows the relation between the number of circuits, the lead diameter and the minimum cluster diameter.

In view of the critical requirements for small size and maximum number of circuits, considerable effort has been expended to effectively reduce the space required by the leads. Lead wire within the capsule is held to minimum size by substitutions of special thin wall insulations or by use of small O.D. magnet wire jumpers (See Figs. 15 and 16). Leads external to the capsule are normally of MIL-W-16878 Type ET construction. This construction offers the minimum diameter combined with ample electrical characteristics for most instrument systems.

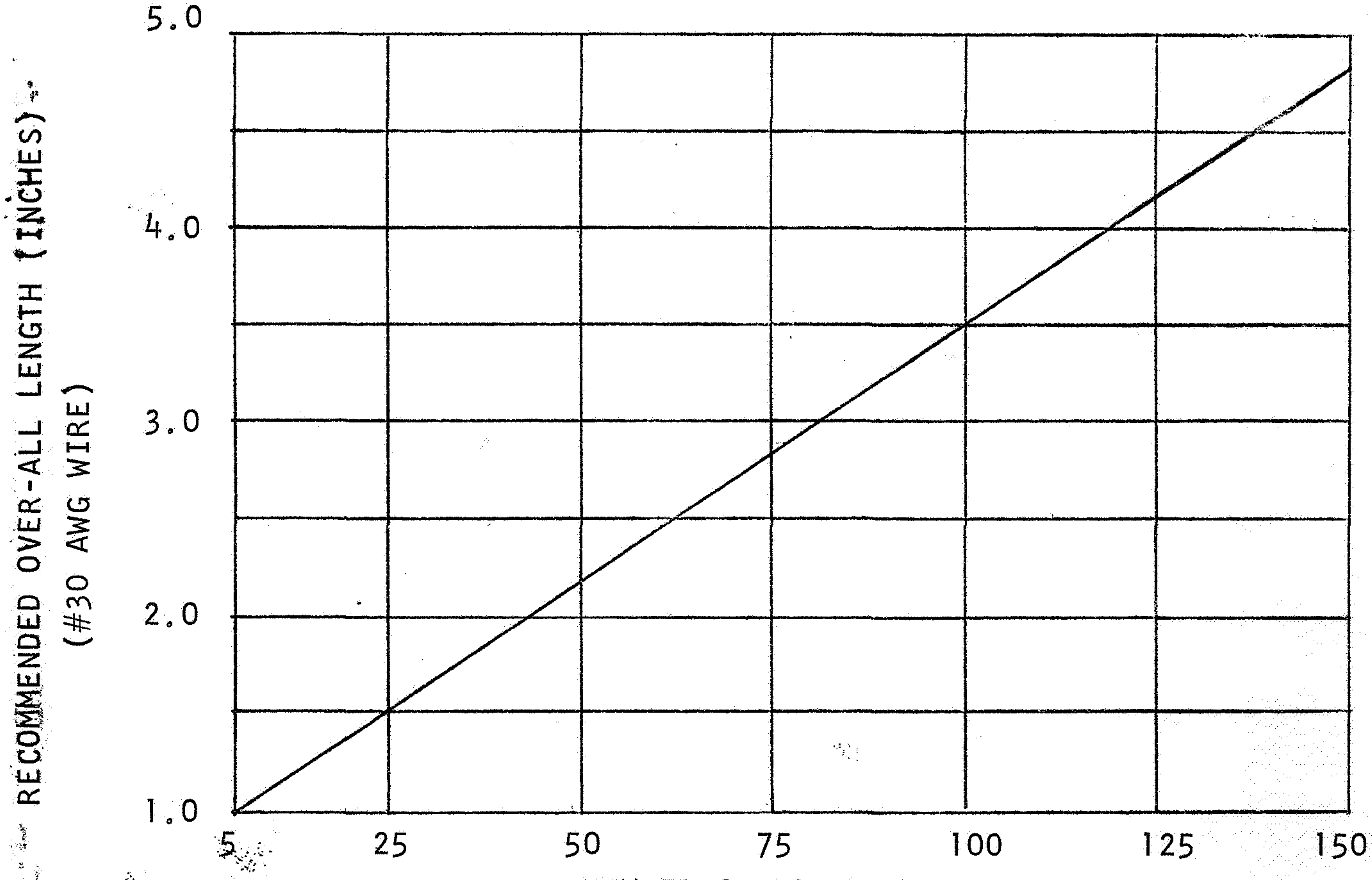


FIG. 12: RECOMMENDED LENGTH VERSUS NUMBER OF CIRCUITS

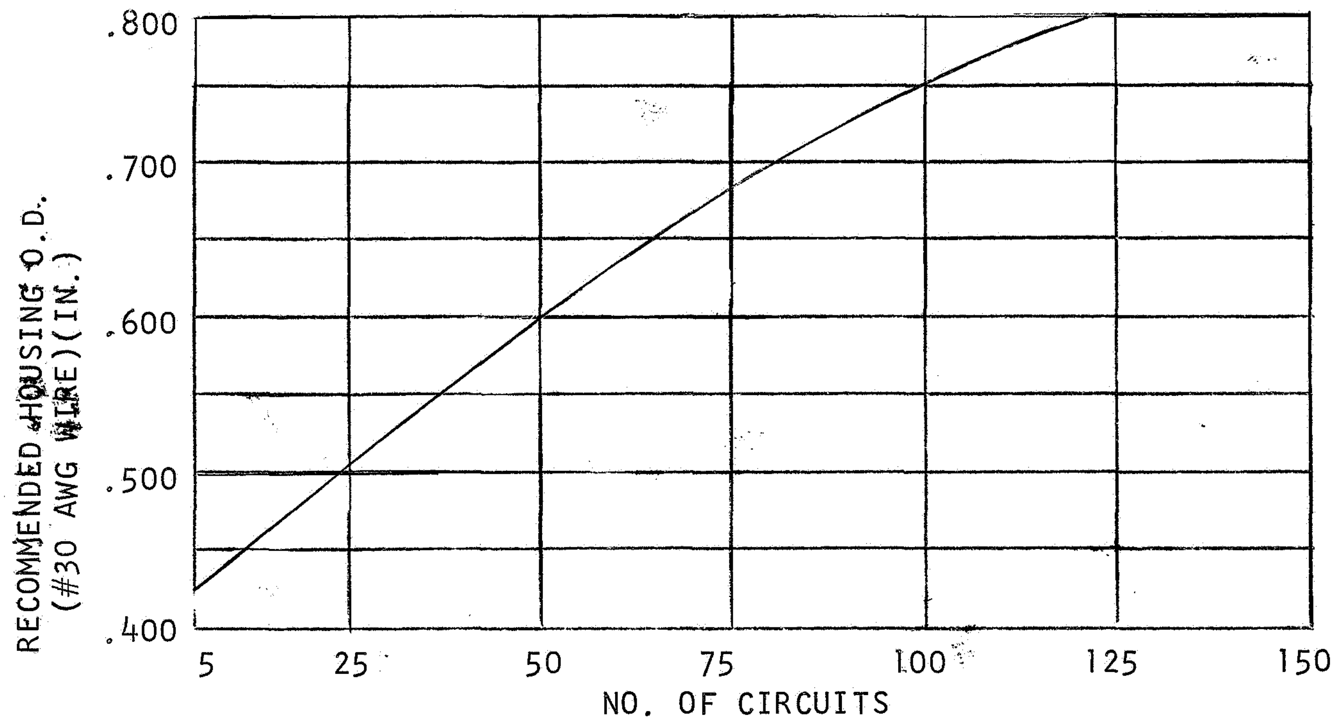


FIG. 13: RECOMMENDED HOUSING DIAMETER VERSUS NUMBER OF CIRCUITS

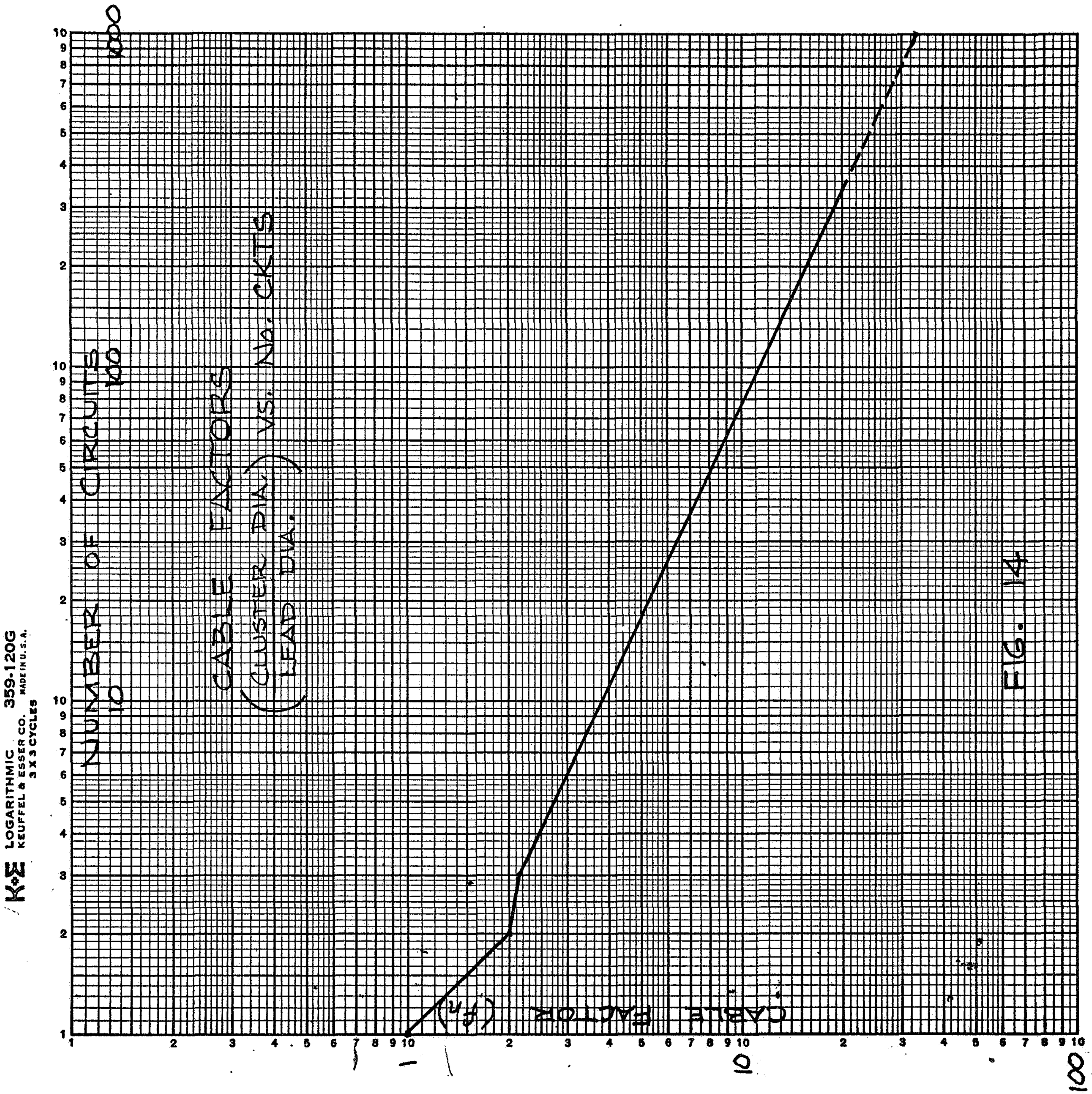

NUMBER OF CIRCUITS
CABLE FACTORS (CLUSTER DIA. / LEAD DIA.) VS. NO. CKTS
CABLE FACTOR (f_n)
K&E LOGARITHMIC 359-120G
KEUFFEL & ESSER CO. MADE IN U.S.A.
3 X 3 CYCLES

FIG. 14

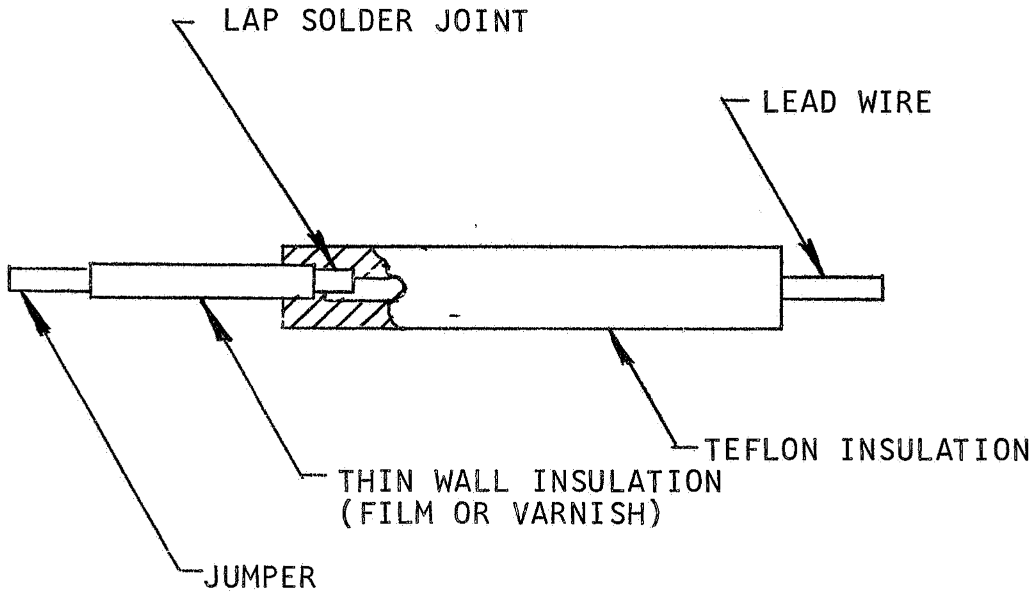


FIG. 15: LEAD-TO-LEAD CONNECTION LAP SOLDER JOINT

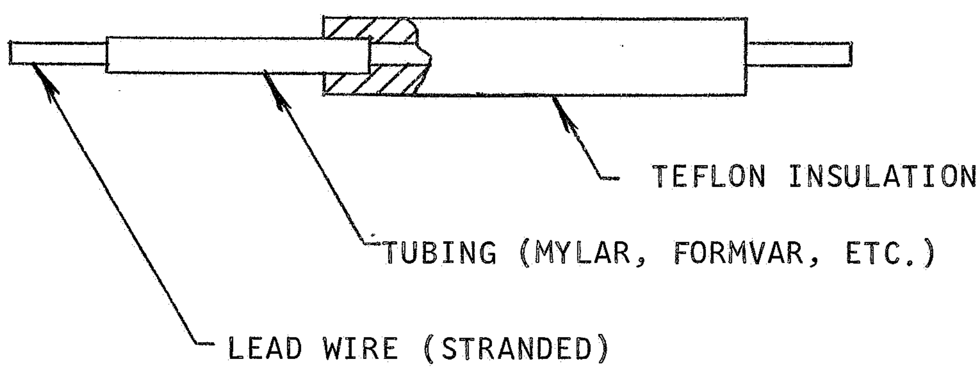


FIG. 16: THIN WALL INSULATION WITHOUT JUMPER

Table IV shows the principal dimensions of Teflon insulated wire. 30 AWG wire normally is used in miniatures because its combination of size, current capacity and handling characteristics make it most suitable in these components.

6.1.3 Capsule Weight - The weight of a completed capsule assembly normally presents no problems. The largest percentage of the weight is accounted for by the leads. The lead length, and consequently the lead weight is normally controlled by the system designer. The next largest percentage of the weight is in the structural members. Due to the miniaturization of the entire component, it is most frequently the space occupied by these members and not necessarily their weight which presents the problem. Normally, there is very little which can be done to control capsule weight, but fortunately this is not critical with most miniature units.

6.1.4 Bearings - Most miniature bearings used in capsule assemblies have crown retainers. Recent work has shown the ribbon retainer to be superior. When a bearing with a crown retainer begins to fail, whether due to contamination, a lubrication breakdown, or brinelling of the balls and races, the resulting roughness can cause one of the ears of the crown to bend outward and consequently lock-up the bearing. Continuous oscillating motions also can cause the crown retainer to bend outward due to the impact of the balls as they shift under the oscillation.

The design of the ribbon retainer bearing avoids any outward relieving of the retainer. Consequently, the possibility of a locked-up bearing is greatly reduced. While the use of a ribbon retainer does not prevent bearing roughness due to contamination, lubrication breakdown, or brinelling of the balls and races, it does greatly reduce the possibility of such a bearing seizing and destroying a capsule (and possibly a system). Although bearing roughness is certainly undesirable in an assembly, it is better than a total failure due to a seized bearing.

Consequently, the use of bearings with ribbon retainers is recommended whenever such bearings can be obtained. There are some limitations on the use of ribbon retainers because bearing manufacturers do not presently supply miniature standard precision bearings of all sizes with ribbon retainers.

Many applications in existence now require bearings other than double shielded bearings due to critical axial length requirements. Enough length should be allowed to include the use of double shielded bearings for several reasons: the shields keep any undesirable products generated inside the capsule away from the bearings and they keep undesirable products from the bearings away from the contacts as well as protect the unit from outside contamination.

TABLE IV - TEFLON INSULATED WIRE DIMENSIONS

AWG	STRANDING	COND. DIA.	EXTRUDED DIAMETER ET	EXTRUDED DIAMETER E	EXTRUDED DIAMETER EE	WRAPPED DIAMETER ET	WRAPPED DIAMETER E	WRAPPED DIAMETER EE	FEP DIAMETER ET	FEP DIAMETER E	FEP DIAMETER EE	AWG
34	1 × .0063	.0063	.018	.026	.036	.018	.026	.036	.018	.026	.036	34
34	7 × .0025	.0078	.020	.028	.038	.020	.028	.038	.020	.028	.038	34
32	1 × .008	.008	.020	.028	.038	.020	.028	.038	.020	.028	.038	32
32	7 × .0031	.009	.021	.029	.039	.021	.029	.039	.021	.029	.039	32
32	19 × .002	.0105	.022	.030	.040	.022	.030	.040	.022	.030	.040	32
30	1 × .010	.010	.022	.030	.040	.022	.030	.040	.022	.030	.040	30
30	7 × .004	.012	.024	.032	.042	.024	.032	.042	.024	.032	.042	30
30	19 × .0025	.013	.025	.033	.043	.025	.033	.043	.025	.033	.043	30
28	1 × .0126	.0126	.025	.033	.043	.025	.033	.043	.025	.033	.043	28
28	7 × .005	.015	.027	.035	.045	.027	.035	.045	.027	.035	.045	28
28	18 × .0031	.016	.028	.036	.046	.028	.046	.046	.028	.036	.046	28
27	7 × .0056	.017	.029	.037	.047							27
26	1 × .0159	.0159	.028	.036	.046	.028	.036	.046	.028	.036	.046	26
26	7 × .0063	.019	.031	.039	.049	.031	.039	.049	.031	.039	.049	26
26	10 × .005	.019				.031	.039	.049				26
26	19 × .004	.020	.032	.040	.050	.032	.040	.050	.032	.040	.050	26
24	1 × .0201	.0201	.032	.040	.050	.032	.040	.050	.032	.040	.050	24
24	7 × .008	.024	.036	.044	.054	.036	.044	.054	.036	.044	.054	24
24	19 × .005	.025	.037	.045	.055	.037	.045	.055	.037	.045	.055	24
22	1 × .0253	.0253	.038	.046	.056	.038	.046	.056	.038	.046	.055	22
22	7 × .010	.030	.042	.050	.060	.042	.050	.060	.042	.050	.060	22
22	19 × .0063	.032	.044	.052	.062	.044	.052	.062	.044	.052	.062	22
22	27 × .005	.030				.042	.050	.060				22
20	1 × .032	.032							.044	.052	.062	20
20	7 × .0126	.038	.050	.058	.068	.050	.058	.068	.050	.058	.068	20
20	19 × .008	.040	.052	.060	.070	.052	.060	.070	.052	.060	.070	20
20	41 × .005	.037				.049	.057	.067				20

Am. Super Temp.

6.1.5 Axial Play and Radial Play - The control of freedom between the rotor and stator is a critical but difficult point to clarify. Ideally, to prevent performance effects upon the contacts, no axial or radial play should be permissible. Axial play affects the longitudinal alignment of the brush and changes can affect wear. Radial play affects the brush force or position. Changes of the alignment in these directions can also affect noise. Excessive axial play will affect capsule performance, particularly under vibration and shock where the effect of end play on noise is most pronounced.

It is therefore apparent that low axial play is more important than low radial play. That is, the radial play has less effect on the performance than the axial play. However, radial play and axial play are related. A bearing with high radial play has less deflection under load, and a higher thrust capability than a bearing with low radial play. Consequently, for low axial play requirements, it is better to use bearings with higher radial play.

Axial play is sensitive to changes of length of rotor and stator due to temperature extremes. Such changes can actually impose preloads to the bearings or create excessive end play.

The opposite of play in the assembly is, of course, preload. In concept, a properly preloaded assembly would have all of the play removed and a small load applied to the bearings which would preclude any play until this load had been reversed by some external force.

This is not desirable in practice for several reasons. Preloads cause deflections in the bearings and other components which contribute to misalignment of the contacts and stressing of bearings and components. The performance of bearings is marginal in the pre-loaded state with the minimal lubrication permissible in capsules. Also preloaded capsule bearings can actually be damaged due to temperature changes and resulting differential expansion. The result is that preloads are not practical for bearings in capsules.

The specific selection and control of end play (or preload) must be based upon the need for brush to ring accuracy and stability, upon the rotor and stator design, and the choice of ball bearings. This play should be defined at a specified temperature, under a predetermined reversing axial test load. For highest reliability miniature assemblies this play is normally .0001 to .0003 inches at room temperature at 100 gram reversing load.

In addition to the considerations above, it is important that the application impose no external loads upon the capsule assembly as a result of the method of mounting. If such supplemental loads must exist they must be carefully considered in the capsule design.

6.1.6 Modes of Motion - Electrical noise and life can be significantly affected by the motion of the unit. Although there is, at present, no known way to quantitatively analyze the significance of the various parameters concerned with the modes of motion, a few facts are known about the effects of the modes of motion.

There are basically three modes of motion which a slip ring capsule assembly might experience in use: First is rotation; second, is oscillation — of either random or fixed amplitude and frequency; and third, is rotation superimposed on oscillation. Under all conditions of motion, surface speeds for wire brushes should be limited to values which will not cause surface damage (40 or 50 feet/minute for gold).

The effect of a motion mode is most often noted in the contact wear and noise. This is the result of the mechanics of the brushes, the traverse of the wiper on the ring and the distribution of accumulated wear debris.

The wiper is caused to flex by the friction force of the contact. At a reversal of the direction of motion this flexure changes, creating an increase of instantaneous contact resistance (noise). Similarly stopping and starting generates noise due to the difference between static and dynamic contact resistance. As the wiper moves across the contact surface, microscopic wear debris is created, some of which adheres to the brush and some to the ring. This is to be expected with any sliding metals with or without lubrication. The brush pushes much of the adherent particulate debris ahead of it. Upon reversal of direction, the change of wiper motion causes some of the debris to be transferred to the ring. Repeated reversals at the same point will create an accumulation of the debris at a point which will interfere with the contact and its continuity on succeeding traversals. Consequently, oscillation is generally agreed to be the most severe mode of motion.

To prevent the compaction of wear debris at one point, by extended periods of oscillating motion, some systems have been planned so that they will be rotated 50 to 100 revolutions every half million oscillations. Such a program also prevents the hardening of organic films and the excessive formation of oxide films which may build up on non-gold surfaces.

At present there is no quantitative method for extrapolating performance data obtained in one mode of motion to one of the others. It is advisable that the actual performance mode be defined as closely as possible to enable use of the best designs and simulated tests for the actual mode. However, a design which performs well in one mode would be expected to perform relatively well in another.

6.2 ELECTRICAL DESIGN CONSIDERATIONS

The slip ring capsule assembly is not a circuit element. It is a closely packed group of transmission lines which happen to rotate. As such, it must be capable of transmitting the signals required of each function with minimum impedance and negligible interference between functions. Just as each transmission line is designed specifically to most efficiently conduct the required signals or power, to a lesser degree so should a slip ring capsule circuit.

In a high performance guidance system slip ring, we might well expect to see heater, motor power, thermocouple, resolver, accelerometer, gyro ground and other circuits. Each function would have its own requirements for current, resistance, voltage, frequency, isolation and interference. Normal practice is to design all circuits of a capsule assembly identically, but a high reliability goal for circuits and capsule would dictate specialized design requirements for each function.

6.2.1 Current - Since each set of circuits may have a different function, each set of circuits will require a different current level. Each circuit can be most efficient only if it is designed for its own current requirements. In addition, all circuits contribute to the heating within the capsule and are dependent upon the total configuration. The circuits current requirement must also be considered collectively in the design of the capsule assembly.

All current limitations on the capsule assembly and its circuits depend upon the relative rates of heating and cooling and the temperature limitations of the capsule assembly and its components. Every portion of the electrical circuits within the capsule generate heat due to current passing through leads, rings, brushes and joints. Heat is dissipated by conduction through leads and mounting surfaces to the system. Normal temperature limitations are based upon the thermal effects on the materials in the capsule: plastics distort, brushes stress relieve, and soft solder melts.

Specifically, the current limitation of a given circuit depends upon the size and material of the brushes and leads. The brush wire has the highest resistivity of the capsule circuit and often the smallest area. The heat generated in the brush must not be sufficient to cause stress relief of the brush wire even with the combination of the temperature rise in the brush and the ambient temperature in the capsule. This defines a current rating for the individual circuit. The current rating for a circuit is that current which the circuit must be capable of carrying on a continuous basis.

The entire capsule must be capable of dissipating the heat generated by all circuits at the same time. This does not mean that the capsule must withstand the combined heating of all circuits each conducting its maximum current. It does mean that the most efficient design of a capsule will be based upon the maximum simultaneous current required. Such a rating can best be expressed as the sum of squares of the maximum simultaneous current of each circuit.

It is feasible to operate a circuit at overload currents of durations less than a few seconds. It is also practical to operate capsule assemblies beyond the maximum total load for a few minutes. This type of performance should be planned into the design.

Finally, it should be noted that the current capability of a capsule depends to a very great extent upon method of mounting, the length of the leads and the ambient pressure and temperature.

With these criteria in mind, it is well to point out that few, if any, miniature capsule assemblies are designed for less than one ampere maximum individual circuit current rating. Most of these capsules are capable of a total load of 1/4 ampere squared per circuit while the best designed units can safely handle 1/2 ampere squared or higher.

For the most efficient and reliable capsule design, the individual circuit current rating, the total capsule load rating and any overload requirements should be defined for the capsule designer.

6.2.2 <u>Voltage</u> - Two voltages are important in the design of a slip ring circuit. First is the operating voltage level of the circuit with respect to ground or to adjacent circuits. This voltage with suitable safety factors is the voltage for which the insulation of the circuit must be designed. As an operating voltage, the circuit must withstand it under all operating environments. The operating voltage is therefore a factor in the choice of lead insulation, barrier material and barrier dimensions.

Second is the open circuit voltage of the function. This is the voltage which would appear across the slip ring-brush contact if the contact were to open. The open circuit voltage is the voltage available, therefore, to break down films which might develop on the contact. With open circuit voltages less than one volt, particular care must be taken in choice and preparation of materials to prevent formation of films under extended life conditions.

6.2.3 Circuit Resistance - Contact member resistance depends upon ring resistance, brush resistance, and contact resistance. In normal applications, the contact member resistance is about 50 milliohms, maximum. Neither contact resistance nor contact member resistance can be measured for a normal capsule.

The circuit resistance is largely determined by the leads, their size, material and length as well as any connectors on the leads. Table IV and V will serve as a limiting guide for wire sizes normally used in miniature slip ring capsule assemblies. The static circuit resistances in a completed assembly are an excellent measure of the quality of the construction of the unit since any bad connections will be revealed.

6.2.4 Frequency - Signal frequencies of instrument slip rings are normally of little concern in the design of the capsule. The only concern regarding frequency in the capsule is that of coupling between adjacent circuits or to ground. When circuits are operated in the range of audio frequency or below, there is only negligible coupling between circuits. If certain circuits will be operated at elevated frequencies or can tolerate only very low coupling, those circuits should be identified for special design consideration.

6.2.5 Capacitance - The electrical capacitance between two surfaces is defined as the ratio of the charge which can be stored between the surfaces to the potential applied to them. Capacitance is not normally a significant problem except as concerns high frequency signal circuits or when crosstalk may become a problem. This is extremely fortunate because there is very little which can be done in miniature capsules to alter the circuit capacitance. The capacitance is dependent upon component sizes and internal spacing which are determined by overall unit design.

The capacitance rating for a unit can only be a rating of the internal capsule capacitance. The lead length, size, and routing of the external leads will have a far greater effect on the capacitance than the internal configuration. Internally the capacitance will be of the order of 100 pf while the leads can have around 400 pf. The capacitance rating is a rating of the capacitance of each circuit to all other circuits and ground.

TABLE V - PROPERTIES OF STRANDED COPPER WIRE

AWG	CONSTRUCTION	NOMINAL CIRCULAR MIL AREA	NOMINAL RESISTANCE (OHMS/FT)	MAXIMUM RESISTANCE OF BARE STRANDED SILVER PLATED COPPER (OHMS/FT)	MAXIMUM RESISTANCE OF BARE STRANDED NICKEL PLATED COPPER (OHMS/FT)	MAXIMUM WEIGHT PER 1000 FEET (LBS)	MAXIMUM O.D. (INCHES)
20	7/28	1111.	.009335	.009806	.001022	3.540	.0381
	19/32	1216.	.008529	.009092	.009672	3.931	.0405
22	7/30	700.0	.01481	.015560	.01662	2.23	.0303
	19/34	754.1	.01375	.014760	.01570	2.448	.0320
24	7/32	448.0	.02315	.02445	.02601	1.435	.0243
	19/36	475.0	.02183	.02363	.02514	1.557	.0255
26	7/34	277.8	.03733	.03968	.04222	.8933	.0192
	19/38	304.0	.03412	.03731	.04100	1.006	.0205
28	7/36	175.0	.05926	.06353	.06757	.5683	.0153
	19/40	182.6	.05680	.06305	.06929	.6140	.0160
30	7/38	112.0	.09260	.10030	.1102	.3675	.0123
	19/42	118.75	.08733	.09855	.1120	.4052	.0130
32	7/40	67.27	.1542	.1695	.1926	.2240	.0096
	19/44	76.00	.1365	.1572	.1787	.2649	.0105
34	7/42	43.75	.2371	.2649	.3010	.1479	.0078
36	7/44	28.00	.3704	.4226	.4802	.09667	.0063

(Hudson Wire Company)

6.2.6 Insulation Resistance - Insulation resistance is the resistance between circuits. It is a function of the design of the assembly, the choice of dielectric materials. It is not normally affected by the insulation resistance of Teflon insulated external leads. In the capsule assemblies many exposed conductors are separated by only a minimum of dielectric surface. The insulation resistance is therefore a function of the surface cleanness of the dielectric material. It is particularly dependent upon the moisture absorption of the plastic, its interfaces and the ambient humidity.

For best design, plastics must be selected on the basis of their volume and surface resistivity in addition to their mechanical, chemical, thermal, and other electrical properties.

Under room conditions (i.e., 20 - 25°C and less than 70% relative humidity) insulation resistances in excess of 1000 megohms can be expected on all designs. Above 85% R. H. when the moisture absorption and surface resistivity of all plastics become significant, the insulation resistance can be expected to decline on miniature capsules. Above 95% R. H. moisture may actually condense on barrier surfaces and damage to the assembly can result from application of voltage.

6.3 PERFORMANCE CONSIDERATIONS

6.3.1 Noise - Noise as observed in a capsule assembly is the variation of circuit resistance. This is of course dependent upon the continuity of leads, and connections, and, most of all, the uniformity of contact resistance. Defective leads with broken strands or imperfectly formed joints can contribute significant noise to the circuit. These, however, are not normally problems in modern assemblies. Self-generated noise is often of great concern to slip ring capsule users. With miniature precision capsules of good design, operating at low speed, this noise is negligible, being less than 10 microvolts. This is the case because contact materials are usually well matched in thermoelectric potential, the low surface speed does not generate high temperatures, and the series arrangement of brushes and rings has a cancelling effect.

The resistance due to the varying path length between the ring joint and the moving brush produces a noise of low frequency. This frequency corresponds to the frequency of the motion between the brush and the joint. This noise is of such low amplitude and frequency as to be insignificant in most applications.

The most significant noise in any contact assembly is the variation in resistance between the contact members. This is created as the moving brush encounters various conditions on the surface of the ring. Such conditions include clean surfaces, surface flaws, wear fragments, films of oxide or organic material, and dust or contaminants. The degree of noise will depend upon the resistance of the condition encountered, its location in the brush path, and the brush dynamics. This type of noise is affected considerably by the mode of motion as discussed previously.

The noise is usually repetitive for a few revolutions at a given point on the ring location. It is generally a pulse or a series of pulses. It will then be wiped away by the action of the brush contact.

Noise can be controlled in design of units by the proper design of brush and ring configuration to minimize the extraneout motion of the contact. The film type noise can be reduced by choice of contact material surfaces. External contamination of contacts can be effectively prevented by assembly under controlled clean conditions. Internal contamination can be controlled by the proper choice of organic materials for use in the assembly. Finally, the noise can be controlled to some degree by the increase of brush force at the expense of greater wear particle formation and higher torque.

Since noise is, in part, the result of the wear particle generation and the formation of contact films, it will generally increase with time. Operating time increases the quantity of wear debris. Static periods allow the formation of oxide or organic films on most materials. It is therefore advisable to plan for some increase in noise as time or life occurs. Capsules stored for an extended period of time should be given a run-in of a hundred or so revolutions before use.

It is to be expected that any sliding metals will experience a deterioration in performance due to operation. This should be realized by slip ring users and a design allowance made in setting forth the slip ring and system requirements. In fact, the requirement should be based upon the system requirement and not an arbitrary maximum. If for example, a noise pulse of 150 milliohms will not affect the system performance, then it is unrealistic to require a 15 milliohms peak-to-peak maximum noise throughout the life test. In fact, the design required to meet the latter value may be beyond the realm of the intended system; in cost, function, and dimensional requirements.

With highest performance capsules, it is reasonable to expect, with high probability, a maximum peak noise level below 10 milliohms when new, increasing to a maximum of 25 milliohms or less after 5000 hours of operation. Some are even being produced which can maintain high probability at 10 milliohm levels for 5000 hours.

6.3.2 Torque - Torque as considered in slip ring capsules is the frictional torque restricting the free rotation of the rotor with respect to the stator. In properly constructed units, it is almost entirely due to the rubbing of the contacts. Torque is a function of the number of circuits, the number of brushes, the shape of the slip ring groove in which the brushes are positioned, the coefficient of friction between the two mating contacts, the brush force, the slip ring diameter, and the environment. Bearings used in capsule assemblies do not significantly add to the torque unless seals are used.

Requirements of a unit which increase the diameter of the finished slip ring sub-assembly have a direct effect on torque. As the number of leads and their size increases, the slip ring diameter increases and torque does also. Use of a reinforcing element in the rotor will increase the diameter of the rotor and, consequently, the torque.

Extreme caution should be used to ensure that the torque requirement and the noise requirement are compatible. Since noise is a function of the brush force and the number of contacts, noise may also be considered a function of the torque. The maximum torque must be high enough to allow the use of contact materials and brush force which will be needed to meet the performance requirements of the assembly. The torque requirement should, in fact, be defined after the other conditions are known, rather than before, to prevent any compromise in performance.

If torque is a particular problem in a given system, then the knowledge of the function of the individual circuits becomes extremely important. Torque may be lowered by using lower brush forces on circuits where the electrical noise requirement is not critical. If the noise requirement is critical, then the use of multiple brushes can greatly increase the noise reliability as long as the torque requirement is compatible; that is, if the brush force of each brush can be maintained and the number of brushes doubled, the noise will be reduced considerably. Too often, when attempting to use multiple brushes it is necessary to reduce the brush force of each brush in order to meet the torque requirements, which may result in an increased number of contacts without a significant reduction in the noise level.

Design estimates may be made by assuming a value of 3 gram centimeters torque per circuit per inch of capsule diameter.

6.4 ENVIRONMENTAL DESIGN CONSIDERATIONS

The slip ring assembly must be capable of performing its required functions within the system environment. This environment includes not only the electrical and mechanical inputs already discussed, but also the chemical, thermal and additional mechanical conditions imposed by the system upon the capsule.

6.4.1 Temperature - Temperature as an environmental factor is important. There are both high and low temperatures which the materials used in capsule assemblies can withstand and thre are limitations beyond which the capsule can not reliably perform. The limitations on the capsule are always more stringent than those on the materials, and usually less stringent than for the system.

Temperature affects preload and axial play of bearings. For all assemblies there are differentials of expansion rate for rotor and stator. Changes of temperature, therefore, will cause differences in the relative length altering the axial play or preload. At low temperatures, this normally tends to tighten the adjustment and at higher temperature to loosen it. Either condition can cause performance effects, if the capsule was not designed for the specific temperature or temperature range.

When considering the upper temperature limit, the temperature rise within the capsule must be added to the ambient temperature. When excessive, the temperature can have a deteriorating effect on the capsule assembly in several ways. The temperature can become severe enough to create internal stresses within the slip ring or brush sub-assembly which will cause failure of the unit due to distortion of the plastic. In addition, the excessive temperature can cause failure of solder joints. Extreme temperatures for long periods can cause stress relief of contact materials and/or relaxation of brush force. Both can produce changes of wear, noise and friction performance. Outgassing tendencies of plastics are increased by increased temperature resulting in a greater organic contamination of the contacts which further affects the noise characteristics.

Circuit resistance also is changed significantly by change of temperature. There is approximately a 20% increase in the maximum DC resistance of the conductor of #30 AWG lead wire over a temperature rise from 68° to 168°F with a similar change at low temperatures.

The problems imposed by temperature extremes can be offset by proper design and materials choices. Most high reliability systems do not impose excessive temperature restrictions on the capsule.

6.4.2 Pressure - The effect of the ambient pressure upon the performance of capsule assemblies is quite significant in several respects.

Reduced pressures in the range between atmospheric and about one millimeter of mercury are normally associated with aircraft altitudes. In this pressure range the reduced air density decreases the convective properties of the atmosphere and reduces the heat transfer from the capsule. Operation in reduced pressures, therefore, necessitates specific provisions for assuring thermal conduction paths for heat transfer. Even with the best conduction paths for capsule generated heat, the capsule must still be derated below its current rating at atmospheric pressure.

The dielectric strength of air is decreased at reduced pressures. The breakdown voltage falls off continuously from atmospheric to pressures of about one millimeter. Below this pressure, the breakdown voltage rises again. The lowest breakdown voltage is about 300 volts and occurs at about the same pressure for other gasses as well as air. Although some solids can also suffer a loss of breakdown strength at reduced pressures, the plastics in use in most slip ring capsules do not decrease in dielectric strength at reduced pressures. Exposed contacts such as slip ring or brush assemblies should not be subjected to voltages above 300 volts at pressures around 1 mm mercury (100,000 ft.).

The lowering of the pressure increases the volatility and the evaporation rate of any material. This causes an evolution of the more volatile constituents from solids and liquids. The same occurs within a capsule assembly. Lower molecular weight polymers are evolved from the plastics. This increases the tendency for these materials to impinge upon precious metal surfaces to form contaminant films or contact polymers. To prevent outgassing of these low molecular weight materials, plastics must be selected for their complete reactivity, be filled to the maximum extent, and be completely cured.

As the pressure is further lowered into the high vacuum range, volatility is increased, reducing the film forming tendencies. Films do not form readily because of the low concentration of molecules. At 10^{-6} Torr., it takes about one second to form a monomolecular layer, thereby limiting the minimum period between wipes of the same area. The effect of high vacuum on both contacts and bearings is high wear rate and early failure. Special precautions can be taken in slip ring capsule design to enable effective vacuum operation, but often at the cost of larger size and higher torque due to seals, special brushes, etc.

6.4.3 <u>Humidity</u> - Moisture on the contact surfaces of the slip ring lubricates and helps to prevent wear. At very low humidity (more than 5%), this lubricating effect is negligible and high wear can result unless special precautions are taken.

High humidity will greatly reduce the capsule assembly circuit dielectric strength and insulation resistance. First of all, moisture is absorbed by plastics under high humidity, causing a reduction of the volume resistivity and dielectric strength of the plastic material. Second, moisture accumulates in microscopic interfaces between components, and between poorly adherent plastic surfaces. This moisture, along with the minute deposits of salts from processing, handling, and the atmosphere, produce surface leakage paths and potential dielectric failures. Third, the moisture is absorbed by particles exposed on the surfaces of barriers between, also reducing the electrical insulating characteristics. Each of these effects contributes to a general electrical insulation reduction during and after prolonged exposure to high humidity.

Below 70% relative humidity at room temperature, there is no significant effect from the atmospheric moisture. At higher values, the effect becomes greater. Prolonged exposure at any elevated humidity increases the moisture adsorption and reduces the insulation resistance. This is particularly acute with exposure to extreme humidity cycling. Extreme cycling can cause condensation on the rings and barriers because of temperature changes and inadequate air circulation in the semi-enclosed capsule. Obviously, water droplets will create electric failures in any device.

High humidity can cause swelling of plastics due to the adsorbed moisture. Filled plastics, in which filler can react with moisture or where the filler is not well bonded to the resin, can be more affected than the unfilled materials. Such swelling will producing warping eccentricities where units are not symmetrical.

Exposure to high humidity can deteriorate bearings and reduce their life considerably. The 400 series stainless steels, required in most bearings for high performance life, are less corrosion resistant than other stainless steels and are susceptable to corrosion. Fretting (rubbing) corrosion of balls, races and retainers is quite probable under extremely humid conditions.

High performance of bearings, plastics and contacts in miniature assemblies is not readily obtainable under all levels of humidity exposure. Exceptional performance under these conditions requires precautions and treatments which can impose severe design restrictions. For this reason, careful consideration must be given the humidity requirements. Since most miniature capsules are components of larger, more complex, and more sensitive systems, humidity requirements should be commensurate with the expected conditions within the system. Also electrical requirements for dielectric strength and insulation resistance must be derated after exposure to non-operating humidity where thorough internal drying has not been assured.

6.4.4 <u>Vibration, Shock and Acceleration</u> - These mechanical environments are well understood by most engineers concerned with components and systems. They are not significant design problems for slip ring capsule assemblies. Although capsule assemblies can readily be designed for several times the requirements imposed upon them by the systems, several points are worth the consideration of the systems engineer.

The most severe mechanical environment is the one imposed by the capsule mounting method. Solid mounting to rotor and stator can impose severe stresses on the bearings and sub-assemblies due to minute misalignment between capsule and system. Loose mounting can allow rotor or stator to move within the system imposing unexpectedly high vibration or shock G levels on the capsule. Ideal mounting is for the rotor (or stator) to be rigidly mounted and the other to be flexibly mounted with clamping. This prevents both undue binding and shock and vibration.

The critical forces on the capsule are motions in the direction and the frequency range which affect the brush force, or of the frequency and direction to move the rotor axially against the bearings. The brush frequency is normally well above the imposed mechanical frequency spectrum. The rotor frequency with more than .001 end play is often within the required spectrum. The permissable G loads of both rotor and brush are far above those imposed by the mechanical environment so that no effect on operation can normally be detected.

6.5 APPLICATION REQUIREMENTS SHEET

To aid the slip ring manufacturer in reviewing the requirements for a slip ring capsule assembly, an "Applications Requirements" sheet has been included. This sheet is a brief summary of the information needed by the slip ring manufacturer for a given design, and if used properly, can become an effective tool in slip ring design development. (A copy is included on the following pages for reference.) See Fig. 16-A and Fig. 16-B)

APPLICATIONS REQUIREMENTS

Sheet 1 of 2

P-S P N ________

PART NO. ________ REV. ________ PROGRAM ________

SPEC. NO. ________ REV. ________ NO. OF CIRCUITS ________

TYPE OF APPLICATION ________

MATERIAL

STRUCTURAL ________

____

LEAD WIRE: CONDUCTOR ________

INSULATION ________

MIL-W-16878D TYPE ______ AWG #______ STRANDING ________

MAX. O.D. (OVER INSULATION) ________

ELECTRICAL

NO. OF CIR.	CIRCUIT FUNCTION	INPUT SIGNAL FREQ. (cps)	CURRENT RATING (amps)	DUTY CYCLE (hrs)	NORMAL OPER. CURRENT (amps)	MIN. OPEN CIRCUIT VOLTAGE (volts)	OPERATING VOLTAGE W.R.T. REFERENCE (volts)	MAX. CIRC. RESISTANCE @ LEAD LENGTH____IN. (ohms)

MIN. INSULATION RESISTANCE: ________ MEGOHMS @ ________ VOLTS D.C.

MAX. DIELECTRIC STRENGTH ________ VOLTS (AC/DC) FOR SEC. (MAX.)________

MAX. CAPACITANCE ________ pf (@ LEAD LENGTH OF _____ INCHES).

CURRENT LOADING ________ CIRCUITS SHALL CARRY THE MAXIMUM RATED CURRENT SIMULTANEOUSLY. THE CURRENT THROUGH THE REMAINING CIRCUITS SHALL BE ________

CONTACT RESISTANCE VARIATION (NOISE)

NOISE TEST CONDITIONS

	ACCEPTANCE	LIFE	SYSTEM
OSCILLATION (°DA/CPS)			
ROTATION RPM			
FREQ. BAND WIDTH CPS			
TEST TEMPERATURE °C			
TEST CURRENT MA			
TEST VOLTAGE VOLTS			
MAX. NOISE - PEAK TO PEAK			

Fig. 17-A

APPLICATIONS REQUIREMENTS
Sheet 2 of 2

ENVIRONMENT:

Normal Operating Environment:	Humidity	____________	%
	Temperature	____________	°C
	Pressure	____________	(Torr.)
	Fluid/Gas	____________	
	Other	____________	
Temperature:	Maximum Non-Operating	____________	°C
	Minimum Non-Operating	____________	°C
	Maximum Operating	____________	°C
	Minimum Operating	____________	°C
	Ambient Operating	____________	°C
Pressure:	Maximum Non-Operating	____________	
	Minimum Non-Operating	____________	
	Maximum Operating	____________	
	Minimum Operating	____________	
Humidity:	Max. R.H.(Non-Oper.)	________@____	°C
	Max. R.H. (Oper.)	________@____	°C
Vibration:	G.(Maximum)	____________	
	Freq. Band	____________	CPS
Shock:	G. (Maximum)	____________	
	Duration	____________	Millisec.
Acceleration:	G. (Maximum)	____________	
	Duration	____________	Seconds
Radiation Dosage:	Gamma	____________	
	Neutrons	____________	

MECHANICAL:

Capsule Weight: (Max.)		____________	Gms.
Housing O.D.:		____________	Inches
Length (Over-all):		____________	Inches
Torque (Max.-Starting):		____________	Gm-Cm
Axial Play:	Maximum	____________	Mils.
	Minimum	____________	Mils.
	Reversing Load	____________	Gms.
	Test Temp.	____________	°C
Radial Play:	Maximum	____________	Mils.
	Minimum	____________	Mils.
	Reversing Load	____________	Gms.
	Test Temp.	____________	°C

Fig. 17-B

7.0 CONNECTIONS

Each connection which must be made from one conductor to another is a potential point for unreliability in a system. The same is true for every component and capsule slip ring assemblies are no exception.

Every capsule assembly has at least two connections; one from the ring to its lead (or terminal) in the slip ring sub-assembly, and another from the brush to its lead (or terminal) in the brush assembly. Additional joints often are necessary in miniature units where small size jumpers are used to connect the contacts and their respective external leads or terminals.

All types of joining processes can be used in these assemblies; soldering, welding, and plating are among the most frequent. The joints within the miniature capsule assembly are all limited in available space. Most are encapsulated in plastic and consequently, when completed, are not self-dependent for mechanical strength.

7.1 RING CONNECTIONS

All three principal processes are used to make ring-to-lead joints; soldering, welding and plating. Each method has its own particular advantages and disadvantages which make it suitable for specific applications.

Many miniature slip ring sub-assemblies are made by a variation of the casting process, and consequently these rings are of the preformed or precut type. The ring-to-lead joints for such rings are normally made by soldering or welding. Both processes are being used effectively, but both can have significant problems in the manufacture of this joint.

Most high precision rings are made of metals with high percentages of gold or silver. Both of these metals form alloys of poor metallurgical quality with the lead in soft solder. The temperature for such joints must be carefully controlled and time of application limited to prevent this intermetallic alloy from forming a poor quality joint with low mechanical strength and high electrical resistance. In addition, residual solder flux can migrate to the ring, causing contact resistance.

These same ring materials have high electrical and thermal conductivity. This creates a difficult set of conditions for resistance welding also. Very high energies are required, causing embrittlement of lead wires without effective welding unless weld conditions are proper in all respects. Sufficient heat for adequate weld fusion can only be produced under carefully controlled ideal conditions.

Where rings are electroformed in place, a process of electrodeposition to the lead wire may be used. This process also requires careful control. Preparation, cleaning, and plating, improperly performed can cause incomplete bonding and inadequate adhesion. Entrapped plating solutions can cause lead or joint corrosion. This particular type of joint necessitates the use of an intermediate solid lead wire to prevent capillary flow of plating solution into the stranded lead wire.

The ring-to-lead joint requires about the greatest mechanical strength during manufacture of any capsule joint. Rings, which are to be cast, must be able to withstand loading into molds. All joints must withstand the differential expansion between plastic and leads and all must provide some mechanical locking against possible rotation of the ring during machining of the ring surface. Most capable manufacturers have developed one or more of these processes to a quality, controllable process.

7.2 BRUSH CONNECTIONS

In most applications the lead is joined directly to the brush by soldering. This is true for both cast and for prestressed brush assemblies. Soldering provides good electrical connection without annealing the brush material. This does have a disadvantage with high gold content brush alloys where the solubility of the brush in the molten solder is high. In such cases, precautions must be taken to prevent poor joints from this solubility.

Resistance welding is applicable to brush joints only where the entire mechanical support is obtained from the surrounding plastic and no mechanical strength is dependent upon the weld. Such joints are principally applicable and desirable where the brush is joined directly to a very short lead or terminal which must be subsequently soldered. Unencapsulated weld joints have not been successful because of the metallurgical transformation occurring in the heat affected zone of the small diameter wire giving a consequent loss of mechanical strength and spring characteristics.

In the junction plate type prestressed brush assembly, the brush is connected directly into a groove in the brush junction bar. This intermediate connecting joint for the brush and its respective lead adds a joint, but provides for encapsulated leads and for accurate brush alignment. (Fig. 11). The brush joint is a solder joint because it provides the entire mechanical support and the electrical continuity to the brush.

When the junction bar concept is utilized, the joint between the lead and the bar must be of a high temperature type to avoid damage to this joint by the subsequent brush soldering operation. Most frequently this is done by resistance welding although high temperature soldering or other processes may be employed effectively by component manufacturers.

7.3 LEAD CONNECTIONS

In several concepts, such as the electrodeposition method, leads must be connected to other leads within the capsule assembly (Fig. 15). Such a joint has traditionally been made by soft soldering. These joints when properly made, are quite adequate provided both leads are encapsulated in plastic for at least three lead diameters and that no other joint will be made in the lead closer than about ten lead diameters.

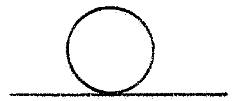
Where leads must be connected to terminals for subsequent soldering operations, the temperature of the first joint must be capable of temperatures at least 100°F above the melting point of the final solder.

7.4 RECOMMENDATIONS

In this section we have mentioned briefly the joints which must be made in every miniature capsule assembly and indicated some of the problems and engineering which must be considered in the design and manufacture of these components. There is no "across the board" answer to the question of how to join two subcomponents. These decisions must be made by the component manufacturer based upon the limitations of the capsule design and the processing techniques available.

It was stated that every joint is a possible point of unreliability. This is still true. It is also true, however, that with adequate processes available to most component manufacturers and with joints encapsulated securely, the failure rate for internal, encapsulated joints is so small as to be of negligible effect in any system reliability evaluation.

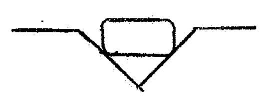
Where outstanding reliability is demanded, rigid controls on processes supplimented by precise circuit resistance measurements on each sub-assembly and/or representative tests can provide additional reliability demonstration for these joints.



(A) FLAT

(B) U-GROOVE

ROUND BRUSH
90°V - GROOVE



FORMED BRUSH
90° V-GROOVE

FIG. 18: CONTACT SHAPES

8.0 CONTACT SURFACE

Because a slip ring capsule assembly must continuously conduct electric current across a moving interface (i.e., the contact) in a uniform manner, the conditions at that interface are of particular importance to the performance of the circuit. Stability, dirt, contamination, finish and wear all contribute to the continuity, or lack of it, in the circuit. The preparation and control of these surfaces are of particular concern to the slip ring engineer and the principles should be understood by the users of these components.

The two major factors in the contact surface design are shapes and finishes. The shape of the ring profile in which the brush rides determines, in part, the constancy, the local brush force and the contamination sensitivity of the contacts. The surface finish determines to a large extent the wear pattern and the contamination sensitivity of the contacts. The contact surface materials have a role in the contact performance and they have been previously discussed. The cleanness and lubrication of the surfaces are also critical to the contact operation. We will now examine each of these concepts in greater detail.

8.1 SHAPE

The shape to be considered for the contacts is the cross-sectional form of the ring surface and the contacting brush at the point of contact. Three rings surface shapes are frequently used in slip ring design; flat, U-groove and V-groove (Fig. 18).

The flat surface was the earliest and is the simplest of the surfaces to produce. This is the outer cylindrical surface of the ring. The flat surface offers no constraint to the sidewise motion of the brush and consequently is readily adaptable to units with extremely loose tolerances between ring and brush. The ring must be wide enough to accomodate the range of brush positions to be expected. The flat ring does not contribute any stability to the brush track and consequently produces the highest noise when used with wire brushes on miniature assemblies. This lack of constraint also allows considerable wear due to the unstable brush track.

The U-groove is a round bottom groove, the radius of which is only slightly larger than the brush radius. This groove constrains the brush to a narrower track but still allows a significant amount of freedom. Like the flat ring, the U-groove has only one point of brush-ring contact. The noise and wear character of the U-groove is slightly better than that of the flat. The tolerance on the groove radius is critical for uniform performance.

The V-groove is a groove with V shaped profile. The radius, if any, at the bottom of the groove is significantly smaller than the radius of the brush. This configuration forces the brush to ride on the sides of the groove, giving two points of contact, one to each side of the groove. These two contacts produce a redundancy of contact and the reaction between the brush force and the groove sides to effectively stabilize the brush from lateral movement. The stability and the brush force both can be increased for minimum noise by reducing the individual angle of the V-groove. Grooves between 60-90° have been found to be optimum in both noise and wear. Because of the force relationships in the contact, the friction is greatest on the V-groove of these three shapes. The V-groove requires the most accurate alignment between the brush and the ring of any of the three configurations discussed.

Most of the brush cross-sections are circular, but a few are being used which are essentially rectangular. The rectangular brushes have no particular advantages when used with a flat or U-groove ring, but these brushes in a V-grooved ring produce a significant improvement in noise performance principally due to the ability of the rectangular brush to operate in the presence of the contamination which inevitably forms from the operation of these contacts.

8.2 SURFACE FINISH

For any geometry of slip ring contact, the most critical performance feature is the nature of the surfaces in contact. Because only recently has theory begun to explain the critically important but totally empirical surface finish problem, the concern here need only be the qualitative concept of surface finish.

From the engineering standpoint, the contact "surface" consists of the materials of the contacts, which during the life of the capsule, may be touched by the opposing member. These surface materials have unique properties and characteristics which can widely differ from those of the bulk metal of the ring or the brush. The surface "finish" is the roughness and character of the surface in the wear track.

The finish originally is the result of the processing of the contact surfaces. For contacts which have been operated for some time, the finish is the result of the wear and transfer of the surface materials under the influence of the sliding conditions. The nature of the initial surface will, with other conditions being the same, determine the character of the sliding surface. For example, a surface which is initially very smooth will, for most contacts, trigger a very severe mode of wear often called galling or seizure with large wear particles and high friction. Once initiated, a severe wear mode will continue indefinitely until the conditions permit the mild wear to be instituted. A uniform surface which has been mechanically roughened will exhibit a mild mode of wear with very small, uniform, wear particles. A mild wear mode, once started, will not change without some external cause.

The exact cause of this particular phenomenon can only be conjectured. It is believed that both the roughness of the surface and an assumed work hardening of a thin surface layer combine to provide a firm track for the sliding brush. It has been demonstrated that a well prepared surface can produce so little wear as to eliminate the necessity for deliberate contact lubrication.

8.3 SURFACE PLATING

The plating of the surface with gold provides an excellent contact surface material, and a means for controlling of surface hardness. As discussed before, gold is the least reactive of the metals thereby offering no oxidation and the least tendancy for the generation of contact polymer.

When the gold is co-deposited with very small quantities of certain elements, the hardness of the plated surface can be raised to values well above that of pure gold or comparable wrought alloys of high gold content. This hard deposit of metal produces an initial contact surface which will have an excellent wear mode. This hard deposit, even in a very thin layer, can result in a long wearing surface. The similarity of the wear from a hard gold surface and a matte finished surface strongly support the belief that the surface hardened nature of the matte finish accounts for the desirability of the process.

8.4 CLEANNESS

In order to effectively conduct an electric current at low voltages, a sliding contact must be "clean". Clean in the sense used here means that it must be free from insulating oxides, free from the particles causing mechanical and electrical interruption of particles, and free from insulating films of high viscosity which can separate the contacting members.

The use of gold effectively and conveniently prevents the formation of oxides provided any base metals in the contacts are sealed off from migration or diffusion to the contact surface.

Protection from particulate contamination is more difficult. Non-conducting debris can originate both within and without the capsule. All burrs and loose particles of plastic in the capsule must be removed prior to assembly and the assembly must be preformed in controlled conditions precluding non-conducting particles larger than the average surface finish height. (The wear particles generated by the normal wear processes are to be expected and are not considered as indicative of part cleanness even though they very definitely affect contact performance.)

The contact surface must be free from films of non-conducting materials, particularly highly viscous ones. Any non-conducting film will intrude into the contact area, increasing the contact resistance to some degree. In a sliding contact, brushes with low force can easily be hydrodynamically separated from the ring by the action of viscous films on the surface. The more viscous the film the greater the effect.

Most of these can readily be prevented on the initial surfaces by careful cleaning techniques. Where lubrication is a necessity, the selection and application can be made to minimize such problems due to oil films.

Most film problems result from the interaction of organic vapors and the precious metal contacts. Such problems are minimized in precision assemblies by use of contacts of the minimum reactivity of high gold content alloys and the proper selection, processing and cure of all organics required in the capsule. The clean conditions are maintained by protective packaging and handling.

It is equally important that the clean conditions established initially in the unit be maintained in the system. All organics used in an enclosed system containing a capsule slip ring must be selected for their low polymerization tendency and their low outgassing rate.

8.5 LUBRICATION

Metal surfaces sliding in intimate contact will undergo wear. The cleaner the surface the greater the wear. Some degree of lubrication must exist to prevent gross seizure of the mating surfaces. Lubrication on electrical contacts will occur from two sources: the first from organic reaction described above and the second from deliberate lubrication of the surface.

With contact materials of the nobility of gold or higher, the presence of plastic materials in and around the contact will normally produce sufficient lubrication for the contacts operating under light loads and reasonably low surface speeds - say under 10-20 feet per minute.

For high forces, very soft materials or high speeds supplemental lubrication should be added to the contact in very limited quantities. The material should have a low viscosity, even in thin films and at the lowest temperatures of operation. The material should not readily polymerize to produce viscous products on the surface.

Quantitatively, the material should be available on the surface in layers only a few molecules thick to enable lubrication without introducing the additional problem of entrapping particulate material into the film and retaining it on the surface.

8.6 RECOMMENDATION

It is believed that most manufacturers have designs and processes which produce adequate contact performance for many applications. Where reliability of performance is the foremost consideration, surfaces should include a V-grooved shape, finished with a removable abrasive compound to about 32 microinches and flashed with 99% gold of at least 150 Knoop hardness. No lubricant is desirable for such a contact.

9.0 CONTACT ADJUSTMENT

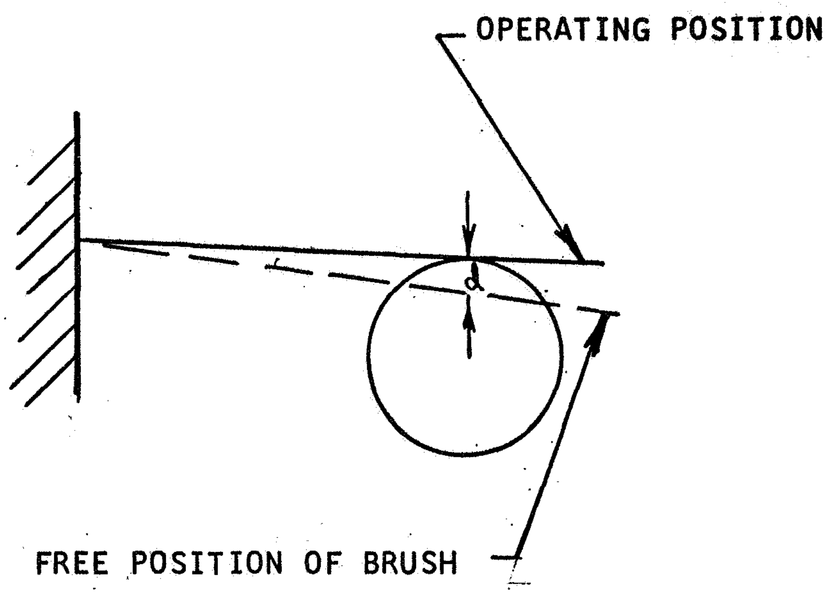
Contact adjustment is the accurate positioning of brush and ring to assure that the contact surfaces will maintain reliable conduction under all anticipated conditions of operation. This includes both the contact force and the contact alignment. The adjustment is normally provided by the manufacturer to the criteria determined by the application. The discussion is included here because it is important that the user understand the criticality of the adjustment and to some degree how it affects the application of the unit.

9.1 BRUSH FORCE

The brush or contact force is the mechanical load maintaining the closure of the contacts. The force enables the brush to maintain a large area of contact so that imperfections and obstructions developed in operation are overcome with a minimum of resistance variation (noise). It also enables the brush contact to mechanically break-down films of oxide or polymer which may characteristically form on the contact surface. Contact force helps the contact to wipe aside wear debris which accompanies contact operation. On the other hand the force causes the contacts to experience both friction and wear. The choice of brush force must therefore be a judicous compromise between the requirements of contact noise, friction, and wear.

In miniature capsules, the brush force is almost always produced by the spring character of the brush which has been deflected by the ring member. (Fig. 19). Because of this, the force on the contact at any instant is greatly dependent upon all of the factors which affect the dynamic operation of the cantilever spring.

Since the force is created by deflection of the spring, the relationship between force and deflection (radial compliance) is quite critical. First, the nominal brush force must be held to reasonable tolerances, of the order of one-half of a gram. To set such a brush by deflection, the compliance must be as large as possible to enable maximum precision of setting tolerance to fall within one or two thousandths of an inch (mils). On the other hand, high compliance (limber) brushes have a tendency to interact with the friction forces at the surface, and develop a "stick slip" motion which produces a cyclic brush force and a cyclic noise. The best radial compliance has been found to be in the range of 4-5 mils per gram.



DEFLECTION (d) IS CALCULATED TO PROVIDE INTENDED BRUSH FORCE

FIG. 19: BRUSH SETTING

Since the brush force is very dependent upon the spring character of the brush, it is important that all brushes receive uniform preparation. It is important that brushes be produced by a minimum of forming and setting operations, because of the effects of supplemental working on the properties of the material. The mechanical forming of the brush to close tolerances, and the use of designs which do not impose subsequent working of the brush contribute to uniform brush performance.

9.2 ALIGNMENT

The misalignment of the brush is the distance between the centerline of the groove and the point of exit of the brush from its mounting. (Fig.20). The misalignment, or alignment, of a brush to a ring is dependent upon the accuracy of the ring groove location to the aligning surface of the slip ring, the accuracy of the brush mounting point to the brush assembly aligning surface, the tolerances on bearings and alignment surfaces, and the straightness of the brush itself. The alignment of the brush to the groove is important for two reasons: (1) brush side loads, resulting from the deflection of the brush sideways to conform to a groove location, will add to the total contact force, increasing friction and wear, and misalignment of brushes and grooves even without side loads will create eccentric friction loads and can result in severe friction moments, high torque and wear.

(The former condition can also occur with aligned brushes and grooves, where brushes have been distorted sideways from their mounting and then are deflected back into alignment.)

The problems which result from either condition are not normally apparent until the unit has been subjected to extended operation or test. In some cases, extreme misalignments may cause brushes to jump out of the groove under severe mechanical vibration or shock.

9.3 INSTALLATION

The accuracy of both alignment and adjustment are determined to a very great extent by the concept and tooling used. The pre-stressed concept of brush permits the most accurate preadjustment of the brush for both force and alignment. Other concepts require adjustment after the brush has been installed in the assembly.

It should be pointed out that adjustment of brushes after installation into the brush assemblies tends to damage the brush surfaces. These nicks and scratches can, depending upon shape and location, significantly impair the designed brush characteristics.

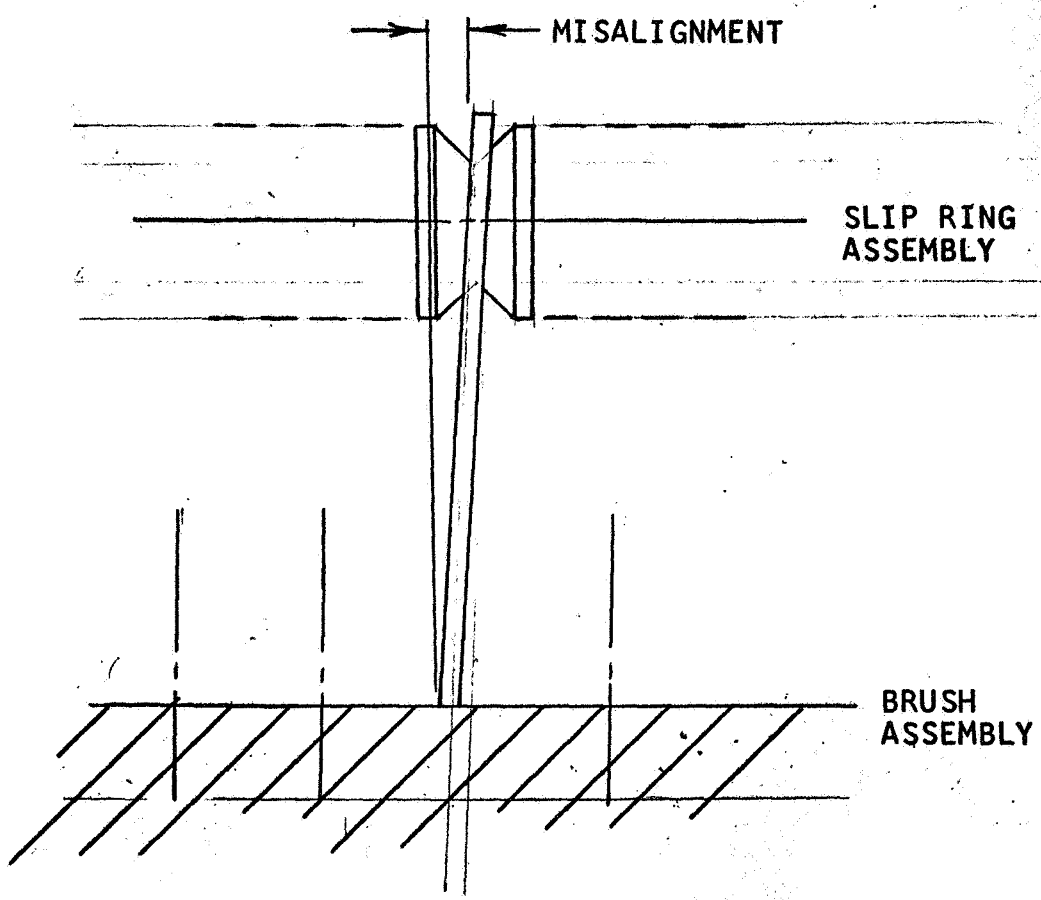


FIG. 20: MISALIGNMENT

9.4 RECOMMENDATIONS

The most effective means for control of brush adjustment is the use of brushes which require a minimum of forming and which in operation have a maximum radial compliance of about 4-5 mils per gram. These brushes can be best aligned by installation into accurately located grooves on both rotor and stator. Careful work can obtain alignments (without side loads) within ± .0015 inches or about one-half of one percent of free length, whichever is greater. Manual adjustment of assembled brushes should be avoided to the greatest extent possible.

10.0 POTENTIAL PROBLEM AREAS DURING HANDLING

A slip ring capsule assembly is a delicate precision component, and as such, it should be handled with extreme care to insure no damage. This section points out the potential areas where problems can arise during handling and installation of the unit.

It is essential to have knowledge of these problem areas and initiate proper action to ensure they are not allowed to affect capsule performance.

10.1 ALIGNMENT OF CAPSULE TO SYSTEM

As mentioned in previous sections of this manual, there is some runout present in completed capsule assemblies. Although this total indicated runout between the rotor and the stator housing is usually held to .005" max. (or less, depending on design), and test apparatus in which the capsule assembly is inserted and tested prior to installation should allow some degree of flexibility in either the rotor or the stator in order to eliminate degrading cyclic stressing of the rotor and bearings during testing.

Additional radial runout in the system between the rotor and the stator should be minimized as the combination of the system runout coupled with the capsule runout may be even more detrimental to the unit. This can be controlled effectively by providing a mount for either the rotor or the stator which will be capable of absorbing the runout without cyclic stress on the rotor and bearings.

For essentially the same reasons as stated above, the perpendicularity between the mounting surface of the flange and the mounting hole for the housing should be held to tolerances at least equal to if not closer than the perpendicularity requirements of the related dimension on the capsule. If this is not accomplished, rotation of the unit will cause cyclic stressing of the rotor and bearings which may result in failure of the unit.

Allowance should be made in both the capsule and the system to ensure that combinations of radial runout of the housing to the rotor and perpendicularity requirements are not detrimental to the unit or the system.

10.2 CLEANLINESS

As manufactured, the slip ring capsule assembly is processed carefully to ensure a completed unit which is capable of satisfactory operation. There can be no guarantee that a unit will operate successfully in the system if the unit, as installed, is not in the same state of cleanliness as at the time of manufacture. The use of organics or other volatile materials in the immediate vicinity of the capsule assembly is not a recommended practice. These vapors have a definite effect on the contacts surfaces when exposed to such vapors.

Precision ball bearings used in capsule assemblies contain lubricant. This lubricant is quantitatively applied as one of the last steps in processing the unit. Any exposure to vapor or immersion in solvent of an assembly during handling and/or installation will affect this lubricant. Consequently, this should be prevented unless the process is known to the slip ring manufacturer, and the capsule assembly has been designed accordingly.

Any soldering operations performed during handling and/or installation should be controlled with extreme caution. Care should be exercised also to prevent solder flux and the solvents used to remove solder flux from coming in contact with the assembly, as both can affect capsule performance considerably.

10.3 TEMPERATURE

Any temperature conditions to which the capsule assembly will be exposed during handling and/or installation should be included and considered in the non-operating temperature requirements.

Some systems require bakeout after completion of the assembly of the system. This bakeout should be defined in the temperature requirements of the capsule assembly.

In some cases, the current requirements on a particular design may necessitate a design which borders on the actual temperature limits of the dielectric materials within the capsule assembly. If this is the case, and the mounting configuration for the system indicates the presence of an available heat sink, then this heat sink should be used in all cases to improve the heat transfer characteristics of the capsule. Modifications to the system should be closely monitored in order to ensure that there is no reduction in the overall effectiveness of this heat sink.

10.4 BEARINGS

When installing a capsule assembly in test apparatus or in a system, extreme caution should be used to transfer a minimum of forces through the bearings. Any brinelling of the balls or raceways will reduce the life of the bearing, and simultaneously the life of the capsule. If the mounting arrangement is such that the housing must be forced into a tight fitting hole or O-ring, then any forces applied to the assembly to install it in the system, should be applied directly to the housing. If the forces are applied through the slip ring then they must be transferred through the bearings. If this is the case, and the forces required are not controlled properly, brinelling will result.

If mounting calls for positioning the slip ring flange on a tight filling member, the force should be applied directly to the flange to prevent force transfer through the bearings.

When installing the capsule assembly, every effort should be made to ensure that in the final location, the bearings are in a "free" position. This can be accomplished by adjusting the capsule axially until the unit rotates as freely installed as it did before installation. This is a very minor precaution to take but it can have a significant effect on capsule performance. As normally supplied by the manufacturer, the bearing take-up adjustment in a capsule assembly varies from lightly preloaded to no preload (some axial play). If the capsule assembly is installed so that the bearing preload is significantly changed by the installation, the capsule performance will be affected.

Due to the tight fit of some mounting arrangements, a hammer has even been used on some occasions to "drive" in the capsule assembly. This practice is detrimental to the capsule because of the uncontrolled shock effects imparted to the unit. Although this can damage other components, the bearings will be the most affected by any such action. Even though the type of hammer can be controlled to prevent any visible external damage, the shock forces are not controllable to prevent internal damage to the contacts and/or the bearings.

10.5 LEADS

In some cases, the leads become the principal means of handling a capsule assembly. This is particularly true if the capsule does not have a flange which provides a convenient means of handling the part. If this is the case, extreme caution should be used in handling the unit since the leads can be easily damaged.

Each lead (#30 AWG or larger) will withstand a two pound pull without tensile failure. The capsule, however, will not stand a two pound pull on all leads simultaneously as the resulting force would damage the precision ball bearings. Control should be exercised to insure that the tensile strength of the leads is not surpassed because of the possible damage to the leads as well as to the internal connections.

The critical flexure portion of the leads is at their exit from the capsule assembly. Manufacture of the assembly requires some flexing of the leads; consequently, by the time the unit reaches the systems engineers or technician, the flex life of the leads has been reduced. Thus, further flexing of the leads should be avoided, if possible.

Sharp bends in the leads should be avoided. The leads can be bent around a radius three times the lead wire O.D. without damage, but a smaller radius of curvature can damage the conductor or create cold flow of Teflon under extended loading periods.

All burrs and sharp corners should be eliminated along the route which the leads must follow through the system. Although any radius will be superior to a sharp corner, radii from .010 inch to .020 inch is sufficient to prevent nicked insulation, unless the lead is crushed against the surface in question.

11.0 FAILURE MODES

The reliability of a component is defined as the ability of the component to perform its intended function for the required period of time. There are two types of functions of the slip ring capsule assembly. First, is the mechanical function when the unit must undergo the required motions without impairing the frictional torque performance of the system. Second, is the electrical function in which the multiplicity of circuits must not produce a failure of any of the variety of electrical and electronic operations of the system. The first type is best considered as overall capsule reliability and the second as an individual circuit reliability. Because of this divergence of function and the variety of electrical requirements, little has been done previously to effectively define slip ring capsule numerical reliability. We shall attempt here to define the modes of failure.

11.1 DEFINITIONS

The following definitions will be used throughout this discussion:

a) Failure - Any performance condition existing in the slip ring capsule which will cause a system (or mission) failure. The following conditions are generally classified as failures regardless of the system response to them: 1) a doubling of the friction torque; 2) an one ohm increase of resistance of any circuit; and 3) a structural failure of any component of the capsule.

b) Malfunction - Any out-of-tolerance performance condition which exists in the slip ring capsule. An instantaneous contact resistance change (noise) or a transient torque condition would be considered malfunctions.

c) Defect - Any out-of-tolerance condition existing at the time of inspection. A dimensional or an appearance condition would be examples of defects.

11.2 MODES OF FAILURE OR MALFUNCTION

12.2.1 Non-operating - The major mode of malfunction of a slip ring capsule assembly during periods of non-operation is a gradual increase of contact resistance. This increase occurs due to the formation of insulating films on the contact surfaces from oxidation of base metal alloying agents in the contacts and from organic transfer to the contact surface. Such an occurrence is to be expected with all slip ring assemblies, but the rate of formation and the level of resistance are determined by the qualities of the materials, design and processing of the capsule assembly, and the environmental conditions. Elevated temperature, high humidity and low pressure will individually or collectively increase the rate of film formation, but low temperature and humidity can reduce the resistivity of the accumulated film. Cyclic variations of these environments will further increase the formation of these films. Most films can be wiped away from the immediate contact surface by a few wipes of the contacts, depending upon the nature and adherance of the film. This type of contact malfunction should be expected and for reliable system performance a program of slip ring rotation should be scheduled after an extended period of storage. For a well fabricated assembly, 50 to 100 revolutions is normally adequate to produce the contact resistance levels of a few milliohms.

A second malfunction which is frequently encountered in non-operating humidity is a loss of electrical insulation capability. During periods of humidity testing above 90% RH, condensation can very often form on the units being tested. Most specifications permit either the removal of condensation from the surface by wiping, air blast, or a brief drying period before electrical test. With a slip ring capsule, which is enclosed but unsealed, these procedures are usually inadequate to remove moisture from the exposed contact surfaces inside the capsule. High voltage electrical tests will certainly cause arcing through the residual moisture and damage to the assembly. This can be a severe problem for miniature units where surface distances between rings may be less than .010 inches. This condition seems to occur in humidity testing only and seldom, if ever, is noted in the field. An adequate stabilization period in the system (or room) environment, say 24 hours, should be provided after exposure to extreme humidity before subjecting the capsule to high voltage tests.

Two non-operating failure modes occur from the handling of the capsule assemblies. First is the damage to small bearings and small diameter slip rings from the weight of long lead wires. The weight of the lead wires very often exceeds by many times the weight of the capsule. When these wires are suspended freely from the capsule, the weight can cause overload to small ball bearings or flexure of the small diameter slip rings sub-assemblies. To avoid this, either lead lengths should be kept as short as possible or provisions should be made to support both the leads and the capsule at all times. Second, failure can occur due to field contamination and cleaning. Capsule assemblies which have become accidentally contaminated can fail because of either bearing torque or high noise if operated in the contaminated condition. Cleaning of such units by anyone other than the manufacturer can result in removal of lubrication, can cause degrading reactions with the materials in the assembly, and may not remove the contamination. To prevent such failures any contaminated assembly should be returned to the manufacturer with a description of the contamination for proper cleaning.

11.2.2 Operating - (Normal Stress) - A frequent type of malfunction is electrical contact noise. Noise can be caused by the build-up of films in the non-operating condition as indicated above which are not detected until the capsule is operated. Noise can similarly be caused by films forming on any infrequently wiped portions of the contact surface. It can be caused by the accumulation of wear product and film debris in the wear track.

The degree to which these causes contribute to malfunctions depend upon the contact design, the applied motion, the atmospheric environment and level at which contact resistance variation becomes a malfunction. A V-grooved ring with a formed brush cross-section, providing maximum clearance and smallest contact radius, will give the best noise performance under all conditions. Rotational motion with minimum reversals and minimum wiped distance is the least severe mode of operation. Oscillation of large amplitude and high speed with fixed end points is about the most severe. Environments containing large amounts of organic vapor contribute heavily to the creation of noise. Fluid filled systems are among the most desirable environments because of their ability to disperse the wear debris. Because of the number of circuits, the variety of causes of noise and sensitivity of the circuits to noise, the contact noise is the limiting factor on the life of the capsule assembly.

To minimize such malfunctions, the slip ring capsule should incorporate as many of the highest reliability features as possible within the space and cost limitations on the capsule. To further reduce the occurrance of noise, a high reliability instrument system should be designed so that all organic materials used within the system have the absolute minimum of outgassing under operating conditions. Also provisions should be made to enable approximately 100 revolutions of the slip ring every 100 hours of operation to disperse debris which might have become compacted at the ends of oscillation tracks or to wipe away accumulated films.

One mode of failure occurs with the rigid mounting of the rotor and stator sub-assemblies to the instrument. This type of mounting forces the bearings of the capsule to align with the main instrument bearings, since the slip ring and its bearings are smaller and less rigid than the equivalent instrument structures. The slip ring thus will distort or fracture, or the capsule bearings will be excessively loaded resulting in failure.

Similar failures can occur when the leads are cabled to the system in such a way as to introduce axial or side loads to the capsule.

A frequent cause of total capsule failure is the failure of ball bearings. Miniature bearings demonstrate a sharp increase in friction torque at the onset of failure. The increase in friction can be severe enough to cause stalling or damage to drive mechanism, damage to slip ring shafts or destruction of the bearings themselves. Crown type retainers can wedge outward between the balls and the outer race. Ribbon type retainers fail by separation of the ribbons from the force of the balls, but these failures occur at less than half the rate of crown retainer types.

The causes of the bearing failures have been ascribed to insufficient lubrication, particulate debris, and improper loading. Insufficient lubrication can result from efforts to maintain bearing lubricant films at minimum levels to avoid recontamination of contact surfaces. Since some bearings have been operated unlubricated for extended periods of time without failure, it is probable that bearing failure will occur only from a combination of inadequate lubrication and contamination or overloading. For maximum reliability, a very light lubricating film applied from a solvent solution of about 1/2 percent of lubricant has been found suitable for bearing lubrication with minimum contact contamination.

Particulate contamination of bearings originating from atmospheric debris or produced by the slip ring contacts can cause bearing failure. The harder the particles, the more severe the effect upon the bearing since small soft metal particles will be rolled out and actually have a lubricating effect on the bearings. Iron particles attracted by residual magnetism are among the most dangerous particulate contaminations causing bearing failure. Double shielded bearings properly demagnetized are the best protection against particulate initiated bearing failures.

Most bearing failures have been traced to overloading, most of which is caused by misalignment either of the bearings in the capsule or of the capsule in the drive mechanism. Internal to the capsule, the misalignment must be prevented by the design and tolerance of the components and bearings must be adjusted to avoid overloading. The installation of the capsule into the system must avoid imposing additional loads on the capsule bearings.

Lead failures, either complete breakage or broken strands, constitute the other major failure mode for the capsule. These failures can be caused by improper design which allows material (solder, plastic, etc.), to flow into the interstices of the stranded lead, stiffening it and creating a limited area of flexure. Similarly, failures can occur in a very short length. When leads are repeatedly flexed in less than about 10 diameters, fatigue of the conductor material can readily occur, creating strand or conductor breakage. This is particularly true with conductors of few strands, or with brittle coatings such as nickel plating.

Failure of the capsule due to wearout of ring or brush components is not an observed failure mode even in the most miniature capsules. Although some wear is to be expected from both components, the normal wear product appears as a fine particulate matter of dull brown or black color distributed at the sides of the wear track or adhering to the brush.

Excessive wear, as evidenced by large, bright particles (either flat or elongated), can produce electrical failures between rings. Such occurances are extremely rare with proper finishes, forces and environment. Any tendency to excessive wear can normally be detected after a run-in test of about 100 hours at representative conditions.

11.2.3 <u>Operating - (Abnormal Environment)</u> - The mechanical environments of vibration, shock and acceleration have negligible effect upon the average slip ring capsule. Most brush contacts will withstand mechanical loads of hundreds of g's, without loss of contact to the ring. The normal 10-20 g vibration and acceleration loads required of most miniature capsules will produce contact force changes of a fraction of a gram. Shock levels of 50 g's can create enough force change to produce detectable noise, but no contact opening failures have been reported.

Round wire brushes on flat rings, under high axial shock levels can move to contact adjacent rings, creating potential electrical shorts. V-grooves and proper alignment will effectively prevent this type of failure due to brush motion.

Under transverse mechanical loads, both rotor and stator sub-assemblies will flex slightly, causing some relative sliding motion between ring and brush and possibly some minor contact resistance variation. With instantaneous axial loads such as vibration or shock there will be some relative axial motion of the sub-assemblies depending upon axial play and bearing elasticity. When severe, the ring to brush alignment may be so affected as to cause brushes to jump onto adjacent rings. This can be prevented by the use of V-grooves for maintaining brush position. Failure of bearings can occur due to brinnelling under severe or prolonged exposure to this action. Both failures can be eliminated with minimum play and proper bearing selection for the intended load.

Structural damage to the components or sub-assemblies has not been experienced with most capsule applications.

Electrical failures, other than noise, on properly designed capsules are very rare. Excessive or prolonged voltages can cause dielectric breakdown on surfaces or through insulations. These failures will normally be associated with low pressure or extreme humidity conditions. When such arcing has occurred, it is often detectable from carbonized area of plastic surfaces.

Over current of single circuits will result in brush force relaxation. Extreme cases of over-current produce brush melting, normally at the center of the conducting portion. Direct shorts of high voltage will produce melting of brushes, arcing, and expulsion of molten material, very often interfering with the performance of other circuits. Over-current through the entire capsule results in discoloration of various components, metal and plastic distortion and melting of solder.

Electrical failures of a capsule are the result of inadequate specification or design of the electrical parameters. Such failures can be prevented by adequate knowledge of the capsule requirements.

Humidity, either excess or inadequate, can cause capsule failures. Humidity in excess of 90% will cause a reduction of insulation resistance and dielectric strength due to absorbed or surface moisture. Capsules should be electrically derated during and after exposure to elevated humidity. Humidity in excess of 75% will increase the rate of contact film formation. Where continued conditions of high humidity exist, frequent contact wiping by unit rotation should be specified. Humidity less than 10% can decrease natural contact lubrication and cause excessive contact wear. Operation under low humidity should be avoided unless proper lubrication has been applied to the contact surfaces.

Temperature extremes are usually causes of failure only in conjunction with other environmental conditions, i.e., current, vibration, shock, humidity, etc. Elevated temperatures and heat from current loads are additive and can result in discoloration of surfaces, plastic, or metal distortions, solder melting, etc. Extremes of temperature can produce differential expansions or changes of adjustment which affect performance.

Vibration and shock effects are greater when the capsule components are subjected to stresses from differential expansions due to undersigned temperature limits. Elevated temperatures will increase outgassing rates for most polymeric materials hastening the increase of noise malfunction and failures.

The useful temperature ranges for slip ring capsules can be designed to exceed most electronic instrument temperature limits. Slip rings with adequate lubrication and frost protection can be made effective at very low temperatures.

Low pressure creates unique failure modes in that it increases the probability of wearout unless proper lubrication for contacts and bearings is provided. Temperature effects too are accentuated by reduced pressure due to loss of convection and conduction through the atmosphere. Since radiation is a small portion of the heat transfer at normal pressures, capsules must be severely derated for current at low pressure or design, and the installation must provide extensive thermal conduction paths and heat sinks to the body of the system.

TABLE VI - FAILURE MODES (NON-OPERATING)

FAILURE / MALFUNCTION	POSSIBLE CAUSE(S)	CORRECTIVE ACTION(S)	PREVENTION
I. Circuit Resistance Increase or Noise	1) Film formation	Rotate unit 100 rev.	Planned rotating every 100 hours, or reduce stringent environment.
	2) Bad connections	None	Supplier controls
	3) Broken leads	None	Check handling and installation for excess handling.
II. Dielectric Failure or Low Insulation Resistance	1) High humidity	Allow unit to dry 24 hours.	Study humidity requirements and/or redesign or plan 24 hr. dry after humidity. Do not bake without supplier consultation.
	2) Condensation	Allow unit to dry 24 hours.	
III. Rough Bearings	1) Absence of Lubricant	Return to supplier for relubrication	Check processes to insure no unit cleaning.
	2) Damaged bearings in handling	Return to supplier for replacement of bearing	Check processes for excess bearing loads due to lead weight, installation procedures, handling, etc.
	3) Contaminated Bearing	Return to supplier for cleaning and lubrication	Check for possible particulate contaminants

TABLE VI - FAILURE MODES (OPERATING)

FAILURE / MALFUNCTION	POSSIBLE CAUSE(S)	CORRECTIVE ACTION(S)	PREVENTION
IV. Noise	1) Film formation	Rotate unit 100 rev.	Planned rotating every 100 hours, or reduce stringent environment.
	2) Bad connections	None	Supplier controls
	3) Broken leads	None	Check handling and installation for excess handling.
	4) Wear processes	Rotate unit 100 rev.	Redesign of capsules
	5) Rough bearings	Return to supplier for replacement.	Determine cause. (See III)
V. Damaged bearings	1) Forced alignment with system bearings	Allow one member to "float" and rigidly mount others.	Check system design.
	2) Inadequate lubrication	Return to supplier relubrication	Determine reason for lubricant absence and correct.
	3) Excess load	Return to supplier for replacement.	Remove excess loads applied to capsule.
VI. Dielectric Breakdown	1) Excessive wear	None	Check environment and capsule design parameters.
	2) Over voltage	None	Eliminate excess potential

TABLE VI - FAILURE MODES (OPERATING)

FAILURE / MALFUNCTION	POSSIBLE CAUSE(S)	CORRECTIVE ACTION(S)	PREVENTION
VII. Broken Leads	1) Excess flexing in short length	None	a) Increase flex length to 20 wire diameters. b) Decrease flexing angle, frequency, load
VIII. Torque	1) Bad bearing	Return to supplier for replacement.	Determine cause of failure (See V)
	2) Excess contact force	Return to supplier for analysis	Return to supplier for for analysis and corrective action.

TABLE VI - OPERATING FAILURE MODES (ABNORMAL ENVIRONMENT)

FAILURE MALFUNCTION	POSSIBLE CAUSE(S)	CORRECTIVE ACTION(S)	PREVENTION
IX. Noise (Vibration or Shock)	1) Excessive end play (Capsule)	Return to supplier for analysis	Return to supplier for analysis & action
	2) Excessive end play (system)	Check system assembly and play, eliminate	See Corrective Action.
X. Noise after Hi-temp, Hi-current, Humidity	1) Contamination and low brush force	Return to supplier for analysis	Same with emphasis on plastics, force, and cleaning
	2) Excessive temperature	Check actual temperature	Correct temperature or respecify.

12.0 RELIABILITY EVALUATION FOR CAPSULES

Reliability measurements for slip ring assemblies have seldom, if ever, been effectively obtained. That data which has been obtained has not been accurate in predicting the performance reliability of slip ring assemblies in use, and data gained for one assembly has been extremely suspect in extrapolation to other applications. Recent work has begun to explain the causes of this unfortunate situation and has pointed the way toward some definition and standardization for the future.

The problem has arisen because most manufacturers and users assumed that the principal mode of failure for slip ring capsules would be the wear out of either the ring or the brush. They further assumed that the principal malfunction mode would be noise resulting from wear particles. In other words, the test for reliability was assumed to be one which created the greater wear; i.e., many revolutions. These tests made little effort to define the conditioning of the part, the mode of operation or the noise criteria required for the system. Of course, this resulted in situations where parts qualified to a specification would not perform in a system and vice-versa.

It is now known that wear-out is not a principal failure mode. It is also known that noise originates most frequently in the insulating debris forming on the contacts. The reliability evaluation must be set-up to incorporate these facts.

Organic material can form viscous or solid deposits on precious metal contact surfaces when static. Oxide films too will form on static contact surfaces. Contact devices which must operate immediately after extended periods of inactivity must incorporate an inactive period into the evaluation test procedure. On the other hand, frictional polymer and wear debris will be generated on moving contacts and contacts exposed to continuous motion should incorporate this feature into the test mode.

12.1 CONDITIONING

Present indications are that reliability test criteria should include both a conditioning mode and an operating mode. The two most realistic conditioning modes are:

a) Static - The capsule assembly should be suitably mounted in a test apparatus for a representative period of time at the operating temperature in the operating atmosphere. Suggested conditions would be: 50°C, dry nitrogen, and 48 hours.

This static conditioning period simulates the conditions optimum for generation of insulating films on the contact surfaces, and it also simulates conditions frequently found in guidance systems utilizing capsule assemblies. It should be required of devices which <u>must</u> perform their function on the first few sweeps after an extended static period. This test will produce the lowest reliability value for the capsule.

b) <u>Running</u> - The capsule should be suitably mounted in the test apparatus and operated for a representative period of time under the operating temperature and atmosphere. The conditions recommended are the same as for the static conditioning. The duration of running should be about 5 hours at 2-10 inches/minute.

This simulates the running conditions optimum to the formation of frictional polymer. Higher speeds tend to produce greater wear, but may decrease polymer formation and effects. The condition also simulates the running speeds of most accelerometer type units.

The conditioning procedure should be selected which best describes the action of the capsule immediately prior to the time of required performance.

12.2 OPERATING MODE

Once the conditioning requirements have been established for the capsule, the motion mode for noise test must be defined. The motion should conform as closely as practical to the use mode of the unit.

Most instrument capsule application requirements will fall into two basic modes.

a) <u>Continuous Rotation</u> - This mode, most frequently seen in accelerometer applications is characterized by continuous rotation at speeds fast enough to effectively rub away films being formed but slow enough to avoid undue wear. This would correspond to a range from one revolution per hour to a few hundred revolutions per minute (about 10 feet per minute).

The noise source to be expected in this type of operation is the accumulation of a conglomeration of wear product and frictional polymer in the groove area. When excessive, the conglomerate will contact the brush altering the resistance pattern with consequent noise. 10 RPM has been found to be a useful test mode for this application.

b) <u>Oscillation with Infrequent Rotation</u> - This mode which is representative of many gimbal operational motions is the more severe mode for most capsules. It is characterized by fixed amplitude oscillation with only a very infrequent sweep of the entire surface. The combined wear debris and frictional polymer accumulates at the ends of the oscillation track, but creates little noise until at a later time the sweep of the brush passes over the debris, resulting in high resistance. In addition, noise can be produced by films forming on the infrequently swept portions of the contact. It is important to this test mode that noise be measured during the sweep to detect noise from the accumulated debris.

The test mode frequently used is a six cycle per second oscillation of six degrees full excursion with rotational sweeps in one hundred hour increments. Wider oscillation and higher frequencies tend to increase the severity of the test mode.

12.3 MEASUREMENT

With the conditioning and operating modes established, the electrical measuring conditions should be defined.

Direct current test signals are preferred for all noise measurements because of its simplicity. Constant current, ripple free, low voltage power supplies providing about 0.1 ampere are quite satisfactory and readily obtained. The variation of circuit voltage drop can then be readily amplified to produce readings in the millivolt range on suitable instruments. AC signals can be utilized effectively when applied to the capsule circuits through a bridge arrangement. This produces a noise modulated AC signal which must be demodulated for satisfactory recording. The use of AC input signals has been found to have no effect upon the measured noise (other than that introduced by the measuring equipment response character). DC signals are therefore to be recommended.

For maximum information about the performance of individual capsule circuits a "single circuit" noise measurement technique is highly desirable (Fig. 21). In this method all leads on the rotating end of the capsule are connected together and at least four circuits of the capsule are used for constant current input from the source 'S' and one circuit for current return. The voltage drop (V) variation across the combination is a measure of the noise of the single circuit since the minimum of four circuits in parallel effectively reduces the "input" noise to a negligible level. By sequence switching, each circuit may be measured in turn. It does have the disadvantage of preventing independent, simultaneous measurement of noise on many circuits.

In order to obtain measurements of nearly equal information and to permit (with adequate equipment) the simultaneous recording of a number of circuits, the "circuit pair" technique should be employed (Fig. 22). Here the circuits of the rotating end of the capsules are connected together in pairs. The constant current is fed through a pair of circuits and the voltage variation (V) is measured. By paralleling current sources and instrumentation, the noise of a larger number of circuit pairs can be simultaneously obtained. The disadvantage here is that one piece of data cannot be isolated to one particular circuit.

The simplest and least desirable method of noise measurement is the "series" test. For this method, all circuits of the capsule under test are wired into single series pattern (Fig. 23). The current is supplied through this circuit and the voltage variation determined. In this test no individual circuit information can be obtained and if the number of circuits is large and the RMS noise is high on individual circuits, this technique will result in a completely erroneous measurement. This method should be avoided.

Recorded measurements are much desired for noise measurements. They permit better determination of both amplitude and character of the noise. Mechanical oscillographic recorders are readily available with useful gain levels and a frequency response of up to 100 Hertz. These instruments will record all of the electrical noise normally significant in electromechanical devices utilizing the out-put of the slip ring capsules. If higher frequency noise data is required, optical oscillographic recorders are available up to 4000 Hertz and oscilloscopes can be used to the megahertz range.

Meters have not proven satisfactory for contact noise measuring because of their long response time. They are also undesirable because of the long time period, short duration character of the noise being measured. Therefore, averaging or RMS techniques cannot be accurate.

12.4 STATISTICAL DETERMINATION

Having once established the conditioning, operating mode, measurement period, and recording technique for the collection of noise performance data, only the evaluation of the data remains. Two types of evaluation should be conducted; the statistical determination of reliability (or failure rate) and the engineering evaluation of the cause(s) of the observed performance.

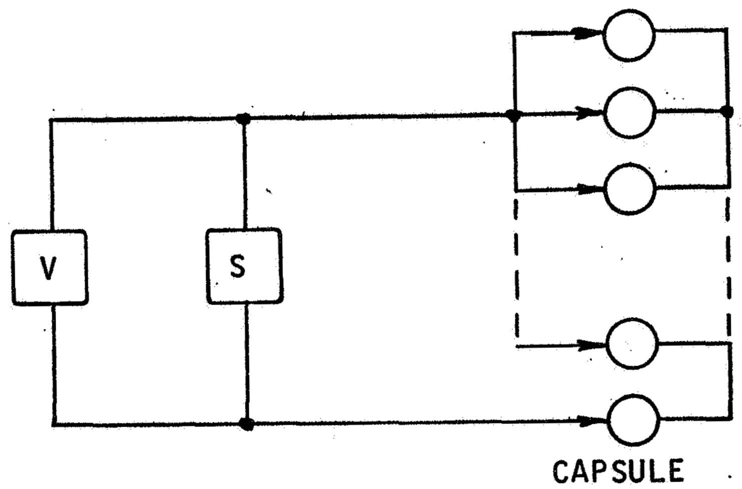


FIG. 21: SINGLE CIRCUIT TEST

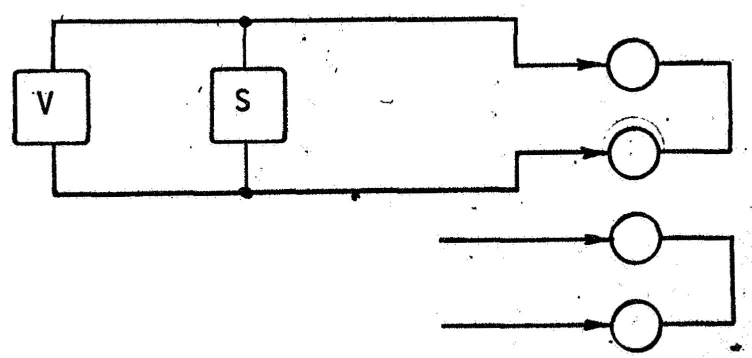


FIG. 22: CIRCUIT PAIR TEST

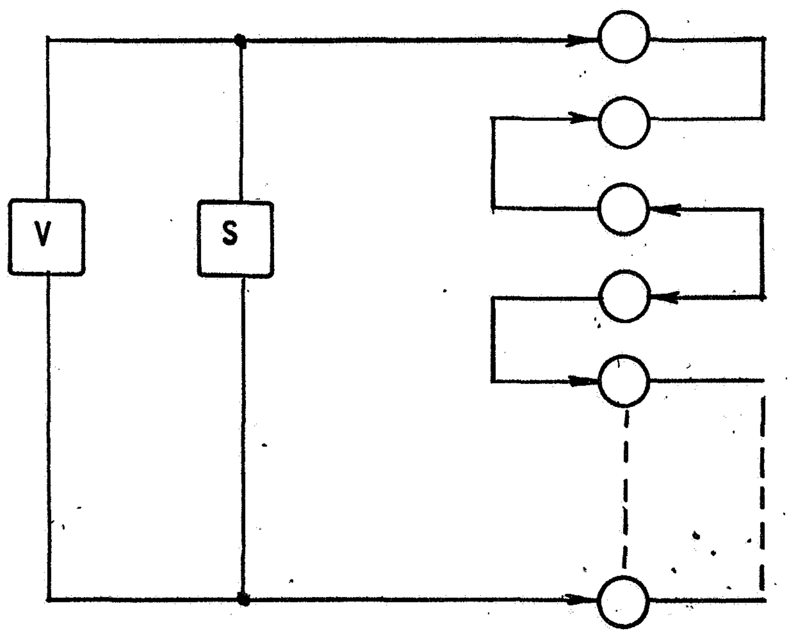


FIG. 23: SERIES TEST

The latter is a painstaking process of testing and dissection to carefully compare each characteristic of performance to the theory, design, and manufacturing requirements of the unit. It is too specialized and subjective process to be considered here on units, and it is best accomplished with the aid of an experienced supplier representative.

The statistical determination can be described briefly. First, a noise level is selected as an arbitrary limit, say 10, 30, or 100 milliohms. If the noise has been measured at regular intervals on any group of circuits, the fraction of circuits exceeding this level can readily be determined for any test interval. By calculation of the fraction exceeding the reference limit for succeeding intervals a graph of percent "malfunctions" with time can be obtained (Fig. 24a). Similarly, by accumulating the data over the total period of time, an accumulated curve can be obtained (Fig. 24b).

Since the proportion of malfunctions at any level is distributed approximately in a normal manner, confidence levels for the binomial distribution can be applied to the data using the proportion and the applicable number of measurements. If the 95% level were desired, a curve of 95% proportion vs. time can be established for the individual test and for the accumulated data. The process can be repeated for other reference noise levels and a % malfunction/time curve developed for the component. (Fig. 25).

From this data can be determined the probability of malfunction during any time.

This information gives the proportion of the tests of a given duration which will be expected to exceed the given noise level. By knowing the total time of testing, the duration of the test increment, and the proportion of malfunctions, the mean time between malfunctions, and the reliability can be determined at the already determined confidence level.

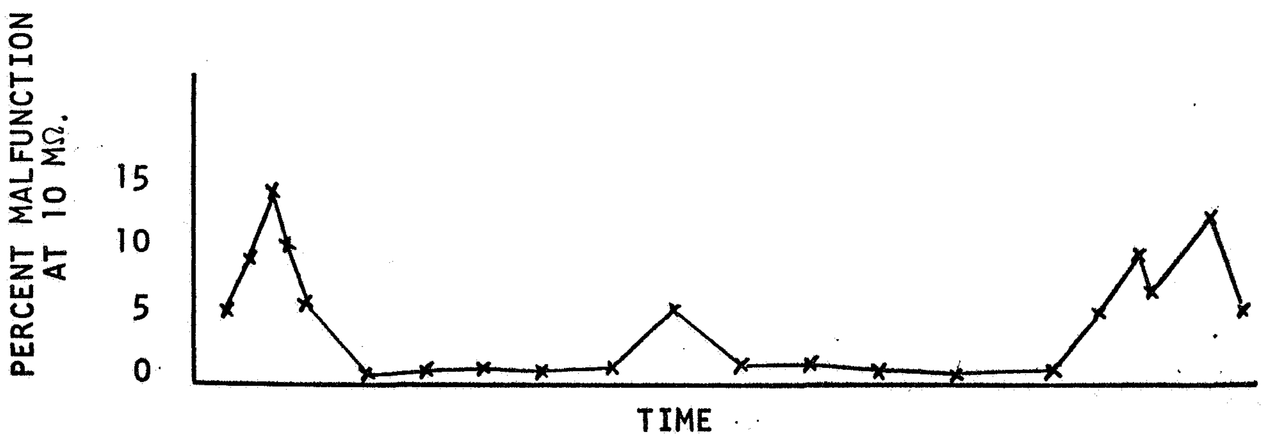


FIG. 24-a

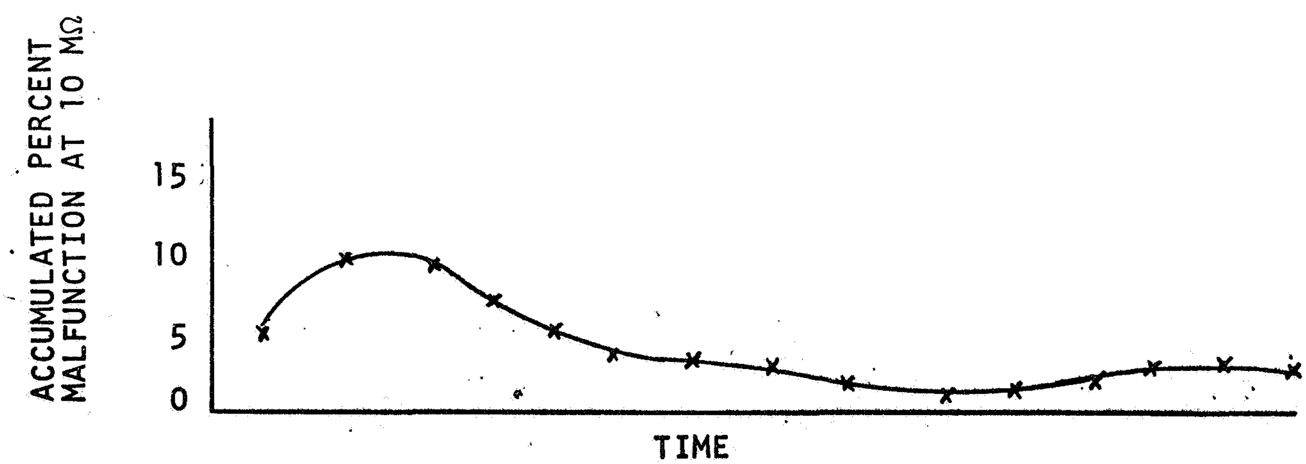
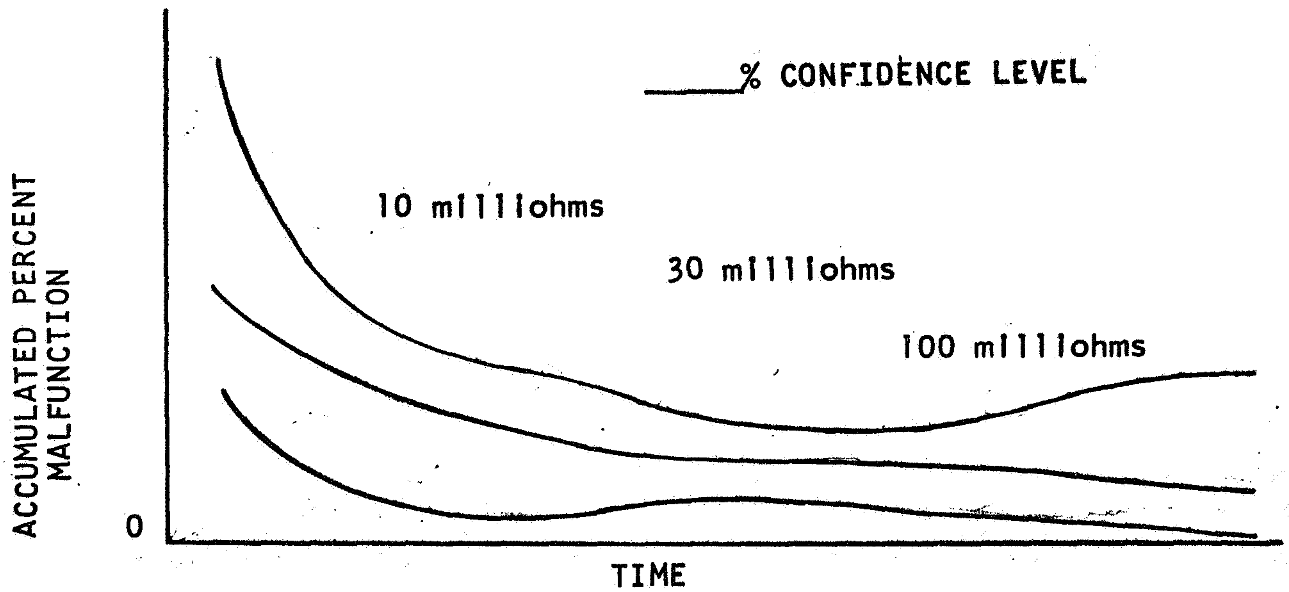


FIG. 24-b



____% CONFIDENCE LEVEL
10 milliohms
30 milliohms
100 milliohms
ACCUMULATED PERCENT MALFUNCTION
0
TIME

FIG. 25